DOCTOR OF PHILOSOPHY

Development of foamed concrete
enabling and supporting design

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DEVELOPMENT OF FOAMED CONCRETE: ENABLING AND SUPPORTING DESIGN

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DECLARATION

I hereby declare that I am the author of this thesis, that the work recorded has been composed by me, all references cited have been consulted, and that it was not been previously used for a higher degree.

Ms. Maziah Mohammad

CERTIFICATE

This is to certify that Ms Maziah Mohammad has done her research under my supervision, and that she has fulfilled the conditions of Ordinance 14 of the University of Dundee, so that she is qualified to submit the following Thesis in application for the degree of Doctor of Philosophy.

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ABSTRACT

Foamed concrete has considerable potential as a material for use in the construction industry. However, although some researches have been conducted on the characteristics of foamed concrete, thus far, knowledge on the behaviour of foamed concrete has been limited. Hence, predictions of the stability of foamed concrete under different conditions and mix constituents have been uncertain. The aim of the presented study is to investigate causes of instability of foamed concrete by examining its rheological properties and microstructure. This study explores the complex causes of instability in foamed concrete by examining the rheological parameters, the yield stress and the plastic viscosity, since the rheological properties affect the hardened state. Using flowability as a guide, the relationships are examined between yield stress and viscosity, specifically with reference to their effect on density and w/c ratio. Other factors affecting the rheological properties related to the proportions and fineness of the mix constituents are also considered.

Thereafter, the microstructure of foamed concrete is examined to establish links with the rheological values and the relationship with stability. The microstructure, best described by the bubble sizes, has been found to be a function of yield stress, plastic viscosity, material fineness and surfactant types. The bubble diameters have been shown to range between 0.1 to 0.5 mm. Bubbles less than 0.35 mm in diameter correspond to stable mix with a drop in level of less than 5% in height in densities of 1000 kg/m^3 and higher. The big bubbles link to unstable mixes and have been found to be a source of instability. Other chemical additions were shown to result in disintegration of bubbles.

As this study unfolds, a relationship is established between bubbles and the yield stress values. Bubble sizes reduced when the yield stress increased. For flowability out of Marsh cone test taken between 1 to 2 minutes, the corresponding yield stress was between 6.0 N/m^2 to 8.5 N/m^2. For this range, the empirical bubble sizes were found to be between 0.33 to 0.35 mm in diameter.

In examining the possible causes of instability, it was found that stability improved markedly with increase in density and lesser effect by other factors such as w/c ratio, constituent materials and specimen height. However, the rate of hardening was a dominant factor in stability as evidenced by the use of Calcium Sulfoaluminate cement, CSA and CEM I 52.5R cement which increased the setting times. Stability was drastically achieved even at lower density 300 kg/m^3. Blends of CSA with CEM I 52.5R and fine fly ash, FA_f, demonstrated similar results.

This research has implications for the development of foamed concrete as a material that could be more widely used in certain construction contexts where stability in lightweight density foamed concrete is crucial. It has contributed to better understanding of the rheological properties and the effect on the microstructure, even though the results are based on empirical values. Hence, it is anticipated that the prediction of stability can be made through a selection of materials and proportions to suit different contexts and their requirements.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Foamed concrete has evolved tremendously from being confined to void fillings only to a variety of construction applications. This development started about 15 years ago, when there was a renewed interest in foamed concrete (Dransfield, 2000). These factors included improved surfactants with better qualities; stronger and more stable without objectionable smell and mould growth problem, improved pre-foaming equipment which allows on-site application to be produced in the back of a ready-mixed truck. The development of this equipment allowed the rapid supply of large volumes and easy supply of moderate quantities to discrete or isolated locations (Aldridge, 2005 and Dransfield, 2000). From Scopus research, the number of published articles on foamed concrete (including aerated concrete and cellular concrete) showed a marked increase since 1998, although some of these articles are not freely available either because they are presented in different languages or are only available through subscribed access (Figure 1.1).

The low compressive strength of foamed concrete is recognised, but it has other advantages such as its high flowability, its capacity to flow readily to fill restricted and irregular cavities, and its ability to be pumped successfully over vertical and horizontal distances. In addition, it requires no compaction. Foamed concrete has low self-weight, with minimal consumption of primary aggregate, controlled low strength and excellent resistance to water and frost, and provides a high level of both sound and thermal insulation (Jones, 2000). With its unique properties, foamed concrete has the potential to be used in various applications in the construction industry. For example, a study by Jones and McCarthy (2005) investigated the potential of foamed concrete for use as a structural material. Since foamed concrete has excellent thermal insulating properties and is lightweight, it can complement other materials to be used in higher strength structural applications (BRE, 2004).

Recent researches focussed on strength in structural use of foamed concrete and also on some of its engineering properties (Jones and McCarthy, 2005a, 2005b, 2005c; Kearsley 1999, Kearsley and Wainwright, 2001a, 2001b, 2002a, 2002b, 2005; Mellin, 1999). Other studies included an attempt to use recycled aggregates from demolition waste (BRE, 2004), the use of foamed concrete as foundations and ground slab (McCarthy, 2004) and other characteristics of foamed concrete (Narayanan and Ramamurthy 2000; Kunhanandan and Ramamurthy, 2006, 2007a, 2007b and 2008). These studies demonstrate that foamed concrete is a versatile material with diverse uses.

This versatility has been recognised by the University of Dundee, where there has been continuous research on foamed concrete covering a wide range of aspects since 1998 as shown in Table 1.1. This figure shows the different aspects of foamed concrete, characteristics that have been considered concurrently and the various approaches to examining the properties

Areas that have been identified that need in-depth study are rheology and bubble structures, including factors affecting their behaviours. Thus, this research will seek a better understanding of characteristics, methods of testing, specification and also engineering properties that will enable and support the design of foamed concrete.

Another area of interest is the causes of instability in foamed concrete. There is a little direct evidence as to why this happens but data from site has proven that instability occurred unexpectedly on-site despite controlled site conditions. In a project in Gerrards Cross tunnel in East London, foamed concrete was selected to top up above incinerated bottom ash aggregate (IBAA) to reduce the self-weight of the total materials above the tunnel (Figure 1.2). This was to facilitate the construction of a Tesco supermarket above the tunnel. There were incidences where foamed concrete collapsed and ‘failed’ about 20 minutes after pouring (Figure 1.3). This unanticipated incidence suggests that foamed concrete has a stability problem which must be resolved, especially at lower densities.

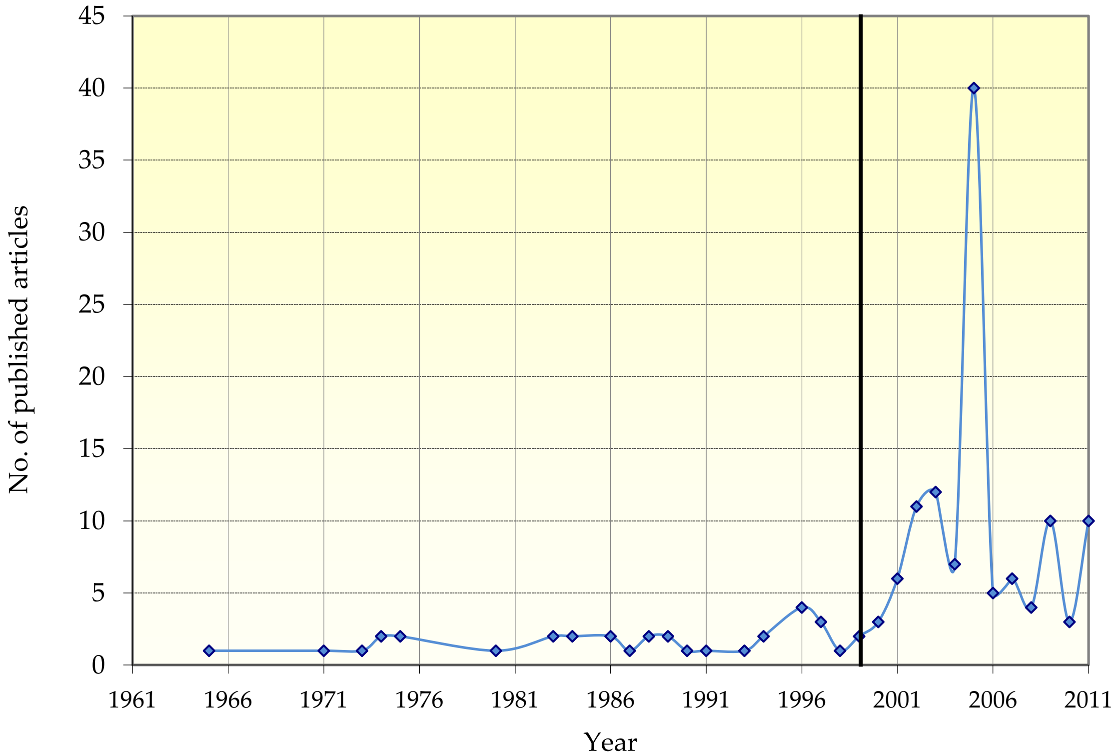


Figure 1.1: Number of published articles

Table 1.1: Researches at Concrete Technology Unit, University of Dundee

RESEARCHER	Zaverdinos 1998	Mellin 1999	Leptokaridis 2000	Madur 2004	McCarthy 2004	Stephen 2006	Rao 2007	Kharidu 2008	Yerramala 2008	Mohammad 2010
OBJECTIVES	Develop structural grade foamed concrete	Investigate effect of fibres on strength development and engineering properties	Develop insulating foundation in low rise building	Effect of fillers on behaviour of foamed concrete	Develop thermal insulating foundations and ground slabs	Investigate formwork pressure and collapse problem using recycled aggregate	Investigate ability to absorb dynamic forces	Develop foamed concrete with no or minimal aggregates content	Design and investigate performance using recycled aggregates	Develop foamed concrete to enable and support design
PROPERTIES INVESTIGATED										
Alkali Silica Reaction					✓			✓	✓	
Sulphate resistance										
Carbonation	✓									
Freeze thaw					✓					
Compressive strength	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Tensile/flexural strength		✓			✓					
Shrinkage			✓	✓	✓					
E-values		✓								
Thermal conductivity			✓		✓	✓				
Consistence/ Rheology		✓	✓	✓	✓					✓
Permeation	✓				✓	✓				
Stability	✓				✓			✓	✓	✓
Fire resistance					✓					
Formwork Pressure						✓		✓	✓	
Heat of hydration			✓		✓			✓	✓	
Bubble Structure						✓	✓			✓
Impact energy										
Use of reinforcement		✓								✓

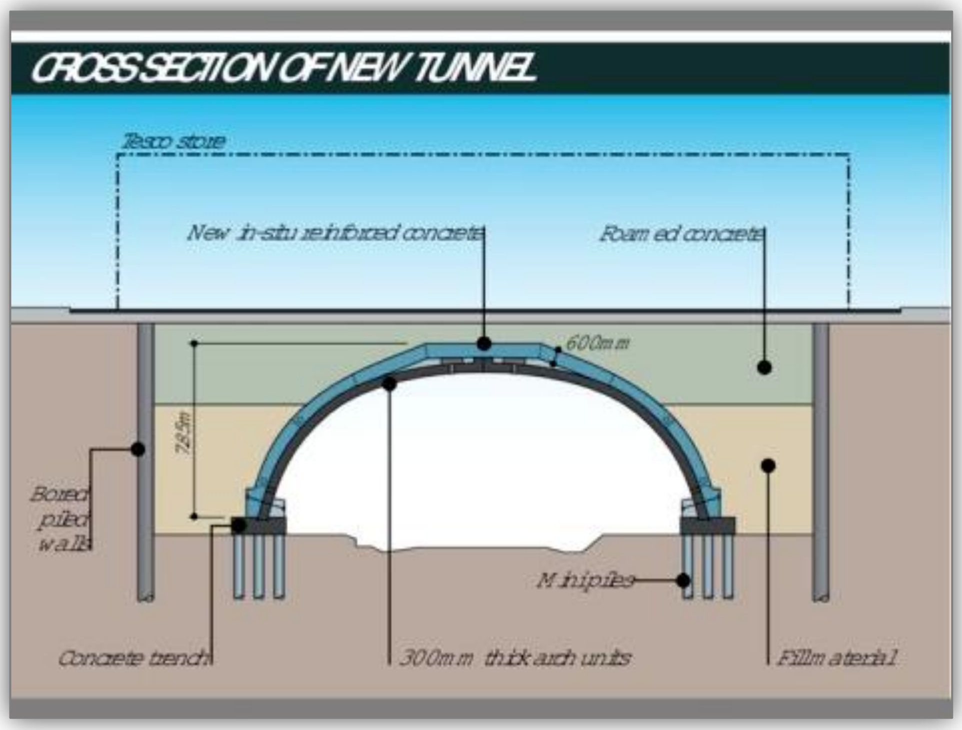


Figure 1.2: Cross section of new tunnel to be constructed at Gerrards Cross

(http://www.nce.co.uk/news/geotechnical/cross-purpose/1995578.article, May 2011)

Figure 1.3: Collapsed foamed concrete in Gerrards Cross project

(Courtesy of Propump Engineering, Ltd 2010)

1.2 OVERALL AIMS AND OBJECTIVES

The overall aim of this research is to study the effect of constituents and mix proportions on the rheological properties and on the microstructural features, affecting the formation of the bubble structures of foamed concrete, particularly in relation to instability. To achieve this, the mix proportions of the constituent materials are examined and corresponding rheological behaviour and the bubble structures are investigated. The method adopted will seek to establish the relationship between the mix proportions of materials to the rheological behaviour and the internal matrix.

The specific objectives of the study are:

i. to find the effect of mix proportion of constituent materials on rheological properties, bubble structures,
ii. to characterise the bubble structures by identifying few parameters and examine the influence of these parameters on the characteristics , and
iii. to study the causes of instability in foamed concrete.

1.3 SCOPE OF RESEARCH

Following the two phases of study, different sets of range were selected. The first phase focussed on the use foamed concrete in structural applications. In this study, foamed concrete was to be produced on a large scale using free falling drum mixer. Since the objective criterion was strength, the target plastic density was 1400 kg/m^3 with 600 kg/m^3 cement content and 0.35 w/c ratio. This density was chosen because it was found that 1400 kg/m^3 is the minimum density at which foamed concrete with coarse fly ash (FA_c) filler could be used in structural elements. FA_c was used in total replacement of sand as filler since the use of FA_c was found to have increased the compressive strength of foamed concrete. Superplasticiser was included to allow the mix to be placed in the beam formwork with ease. In this phase, the scope was confined to a specific design mix and beam dimensions which were a repeat from previous research done in the Concrete Technology Unit, University of Dundee.

The studies in the second phase were inter-related. Basically, the rheological values were measured from fresh foamed concrete mix. The measured rheological values were yield stress, plastic viscosity and flowability, even though the main measurements centred at the first two parameters. The measurement of yield stress and plastic viscosity was done using two-point tests, thus, Brookfield Viscometer and the flowability test was done on Dundee modified Marsh cone. The rheological measurements were confined to typical laboratory conditions. Subsequently, 24 hours after placing the sample materials in selected moulds, the stability was observed from the drop in level. After hardening, the microstructure of the specimens was examined. In order to disregard inconsistencies in making assumptions and generalisations, the examination of the microstructure was performed by an examiner. Basically the same set of mixed was studied throughout. The main range of densities was from 600 kg/m^3 to 1400 kg/m^3 and w/c ratios from 0.4 to 0.6 even though for each study, there were slight variations in densities and w/c ratios. The main cement used was CEM I 42.5N and other variations included Rapid Hardening Cement (RHPC), Calcium Sulphoaluminate (CSA) and CEM I 52.5R for the study of instability. These cements were included to investigate the effect of hardening time. Additionally, other cementitious materials were included as part cement replacement to observe the effect of fineness on the properties. These included metakaolin and fine fly ash (FA_f). The common filler used was sand (fine aggregate) with brief inclusion of coarse fly ash (FA_c) as sand replacement. Two types of commercially available surfactants were used in the study: protein and synthetic surfactants although the more commonly used were the protein surfactants.

The selection of materials was based on the choice of parameters studied. It is anticipated that these will assist future researchers to design foamed concrete mixes to suit their own conditions.

1.3 OUTLINE OF THE THESIS

Chapter 2 provides a review of the literature, summarising the properties of commonly used materials in the production of foamed concrete, the fresh and the hardened properties.

Chapter 3 describes the materials used in the study, the mix proportioning and the standard procedures which were common to the different studies. Different test procedures for each study were described in its own chapter.

The study of foamed concrete beam is described in Chapter 4. This chapter illustrates the behaviour of reinforced foamed concrete beam in an effort to develop structurally viable foamed concrete as a structural material. It explains how a full scale foamed concrete beam was casted and post-tensioned using glass-fibre reinforced polymer rod, GFRP and how GFRP was used for assessment in a more practical way.

Chapter 5 describes the study of rheological properties of foamed concrete. This chapter illustrated the methods employed to achieve the rheological measurements: yield stress, plastic viscosity and flowability.

The technique employed to study the microstructure of foamed concrete is illustrated in Chapter 6. In this chapter, the effects of variations in materials and proportions the characteristics of the microstructure are examined. The diameters of the bubbles are tabulated, where possible. The main range of densities and w/c ratios are similar to those explained in Chapter 5, although brief illustration of the characteristics of lower density is included.

Chapter 7 describes the causes of instability of foamed concrete mixes. It is in this study that another cement type, CSA is included and blends with CEM I 52.5R and FA_f are observed.

The results of each study are explained at the end of each chapter; Chapters 5, 6 and 7. However, the analysis of the results is discussed in Chapter 8. This chapter combines the results and the hypotheses used to describe the phenomena.

Chapter 9 draws the conclusions of the overall study and provides suggestions for future work in this area

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

Foamed concrete is a new generation of lightweight concrete that is versatile with some attractive characteristics such as its flowability, self-compacting and self-levelling nature, low dimensional change and ultra-low density. In addition, the material can be designed to have controlled low strength, excellent thermal insulation properties, good load-bearing capacity and can be easily re-excavated, if necessary. Foamed concrete was generally used for application for ground works such as high volume void fills, reinstatement of utility trenches, road sub-bases, soil stabilisation and grouting tunnel walls. With the advent of improved techniques and foaming agents, the use of foamed concrete has grown more rapidly than any other "special" concrete products, such that the current estimated UK market is thought to be close to 1 million m^3 annually (Aldridge, 2005). This development in the use of foamed concrete has attracted many researchers throughout the world to explore new ideas and opportunities in its application.

Although the research in foamed concrete has been sporadic, there has been some recent interest in the compressive strength and the use of recycled materials. Nevertheless, even after some years of such research, there is still a lack of study of certain characteristics and behaviour of foamed concrete. The main areas in this research are centred on its microstructure and rheological properties which, although they may appear as separate studies, are interdependent and linked to instability. The stability of foamed concrete is of paramount importance as the versatility of this material lies in the ability to control the low densities which is the most fundamental characteristic.

This literature review examines the current knowledge on foamed concrete, including parameters which contribute to the characteristics and behaviour of foamed concrete.

2.2 DEFINITION

Foamed concrete can be defined in two groups of concretes. The first of these is the class of lightweight concretes, while the second is the class of concretes containing air.

In the case of lightweight concretes, the defining criterion is the dry density. This density range is from 300 kg/m^3 to 2000 kg/m^3 with corresponding cube strengths from 1 to over 60 kN/m^3. Included in lightweight concretes are no-fines concrete, aerated concrete, foamed concrete and lightweight aggregate concrete (Newman and Owens, 2003). This definition is limited to concretes containing intentionally entrained voids in the hardened cement paste or mortar. These concretes are referred to as air-entrained, aerated, aircrete, cellular, gas, foamed or foam concretes. Aerated concrete is produced by introducing gas bubbles into the cement paste by adding aluminium powder which reacts and forms gas bubbles which expand in the concrete. Hence, it is also known as gas concrete.

Another type of lightweight concrete which is designed for factory production is the concrete that is cured in steam at atmospheric pressure or in steam at 180^0C under high pressure in an autoclave. This concrete is autoclaved aerated concrete (AAC) which is also known as aircrete. AAC has higher strength, volume and stability compared to non-autoclaved concrete; it is highly reactive but limited to specified mould and to factory production.

Foamed concrete is also classified as lightweight concretes. Also known as cellular concrete, foamed concrete is produced either by the pre-foaming method or the mixed foaming method. The pre-foaming method comprises producing base mix and stable preformed aqueous foam separately and then thoroughly blending the foam into the base mix. In mixed foaming, the surface active agent is mixed along with the base mix ingredients. During the process of mixing, foam is produced resulting in a cellular structure in the concrete. In both methods, the foam must be stable during mixing, transporting and placing. Based on this criteria, foamed concrete is defined as "concretes weighing from 200 to 1600 kg/m^3 (dry densities), having homogeneous void or cell structures" (Valore, 1954).

The second category of foamed concrete is that group of concretes containing air in the hardened cement paste or mortar. In this category are structural air-entrained concrete, highly entrained concrete or mortar (also known as 'controlled low strength material'), autoclaved aerated concrete and foamed concrete (Dransfield, 2000). The variations in this category are shown in Table 2.1. Thus, foamed concrete can be further defined as "highly aerated mortar with air content greater than 20% by volume of mechanically entrained foam in the plastic mortar" (Van Dijk, 1991). This definition is also used by The Concrete Society (2009). This differentiates from air-entrained concrete which has much lower volume of entrained air (Highways agency and TRL, 2001). Dhir et al. (1999) defined foamed concrete as "a cementitious material, where air is entrained by the mechanical incorporation of a preformed foam or admixture into a mortar". For consistency, the term 'foamed concrete' is used instead of foam concrete which refers to the same material.

Table 2.1: Different types of concrete containing air

		DENSITY kg/m3	TYPICAL COMPRESSIVE STRENGTH	BASE MATERIALS	ADDITIONS	CURING	TYPICAL AIR CONTENT	AIR INCLUSION	TYPICAL USES
1.	Structural Air Entrained Concrete	2200 to 2300	30 to 40 MPa	Cement, sand, coarse aggregate	Air entrained admixtures	Normal water curing	5.5%	Direct addition of air entrained to mixture	Freeze thaw resistance, reduced bleeding
2.	Highly Air Entrained Concrete/Mortar (controlled low strength material)	1850 to 2000	3 to 8 MPa	Cement, sand (coarse aggregate, fly ash, Limestone)	Air entrained admixtures	Normal water curing	20 to 25%	Direct addition of air entrained to mixture	Trench and void fill
3.	Autoclaved Aerated Concrete	400 to 700	2.5 to 8.0 MPa	Cement, sand	Aluminium powder	Autoclaved at high temperature	70 to 85%	Addition of aluminium powder admixture that reacts to form hydrogen bubbles.	Light weight precast elements including thermal insulating blocks
4.	Foamed Concrete	800 to 1600	<1 to 8 MPa	Cement, sand	Foam from surfactants	Sealed curing	35 to 65%	i. Preformed foam ii. Mix foaming	Trench and void fill

2.3 SPECIFICATIONS

In the UK, the first specification which included foamed concrete was initiated by the British Cement Association in 1991 (BCA, 1991). Other publications by BCA published between 1991 and 1994 stated the properties, advantages, recommendation for applications, guidelines on strength, minimum thickness where applicable. As foamed concrete was earlier known for void fillings and underground works, these publications were aimed at specifying the use of foamed concrete for trench reinstatement. However, a major step was followed the Horne Report which resulted in a new Act being passed in Parliament which required all utilities making openings in highways to reinstate to a given standard depending on the excavation and method of reinstatement. Following this, the Highway Authorities and Utilities Committee (HAUC) drew a specification for the Reinstatement of Openings in Highways in 1992 which was later approved as a Code of Practice which included an Appendix entitled 'Foamed Concrete for Reinstatement'. This took effect from January 1st 1993 (Chandler, 2000).

In 2001, assisted by the Concrete Technology Unit (CTU) in the University of Dundee, the Highways Agency and Transport Research Laboratory published an application guide AG39: Specification for foamed concrete. In the more detailed specification, the guideline covers the properties, quality control and acceptance criteria (Highways agency and TRL, 2001). Additionally, the CTU, together with industry partners, had also studied foamed concrete and developed fundamental understanding of the material (Jones et al., 2005).

Other specifications in the UK include a specification on the use of foamed concrete as reinstatement material by the UK Water Industry in 1995 (UKWIR, 1995) and the use of foamed concrete for insulating foundations for buildings (Jones, 2004).

These developments have not been confined to the UK. An industrial standard has been identified in Japan: Japanese Industrial Standard (JIS A 1162:1973) entitled Testing Methods for Volume Change of Cellular Concrete. However, the actual standard is not available to date, although it has been mentioned in a literature (IKRAM, 2004).

2.4 CONSTITUENT MATERIALS

Foamed concrete is actually foamed mortar, where the mortar is made from cement and water or cement, sand (fillers) and water. It does not contain coarse aggregates and it is manufactured by adding preformed foam to mortar mass. The amount of preformed foam controls the density of the final concrete.

2.4.1 Cement

2.4.1.1 Portland Cement

In foamed concrete, ordinary Portland Cement (PC, conforming to BS EN 197: Part 1: 2000) is the main cementitious component of foamed concrete (BCA, 1993). The total cement content usually lies within the range of 300 and 400 kg/m^3. Cement content up to 500 kg/m^3 has been used to attain higher strengths, above which, the gain in strength obtained was found to be minimal (Jones, 2000). However, other types of cements have also been used by several researchers (Kearsley, 1999; Highway Agency and TRL, 2001; Aldridge, 2000; Jones, 2005). For example, rapid hardening Portland cement (conforming to BS 915:1983) has also been used in foamed concrete to improve strength development rates at early hydration stages and ultimate strength values (BCA, 1994).

2.4.1.2 Fly ash

Fly ash (FA) has been used as an alternative component of foamed concrete. For example, it can be added to foamed concrete mixes as partial cement replacement (fine FA) and as fillers (coarse FA), replacing fine aggregate. Jones (2001) reported that when fine fly ash (FA_f) was added at levels up to 80% by mass cement, it was found that it reduced cost, enhanced the consistency and mix stability and contributed to long-term strength. The additional beneficial effect of using fine FA was that it reduced the heat of hydration, which is important as foamed concrete has high thermal insulation characteristics (Jones, 2005). In a more detailed study, Jones (2006) noted that, with the addition of fine FA, the behaviour of foamed concrete followed the patterns of normal weight concrete and, furthermore, there was retardation and reduction in peak temperatures. Hence, measures should be taken to account for the reduced early strength gain with slower reacting material, when concreting at low temperatures

(McGovern, 2000). This is attributed to the dilution of PC with fine FA which established slower reactions and prolonged the dormant period and which ultimately retarded the hydration. On the other hand, when FA was used, there is instability in the foam, causing it to collapse (Jones and McCarthy, 2006).

2.4.1.3 Ground granulated blastfurnace slag

Ground granulated blastfurnace slag (GGBS, conforming to BS 6699:1992) has also been used in foamed concrete (Aldridge, 2000a). Similar to fine FA, the strength development was higher in the longer-term (Wimpenny, 1996). However, the mix was observed to be unstable where the bubbles coalesced and consequently the foam collapsed. Segregations have frequently been observed with a number of surfactant types using this material and Jones (2000) attributed the probable cause to chemical interaction between GGBS and foam.

2.4.1.4 Silica Fume

Silica fume were found to have little effect on shrinkage of foamed concrete (Narayanan and Ramamurthy, 2000). The addition of condensed silica fume (SF) up to 10 per cent by weight of cement significantly increased the strength of foamed concrete, where the foam content is less than about 30 per cent (Kearsley, 1996; De Rose and Morris (1999). However, for higher foam contents, the improvement in strength was minimal. Silica fume liberated much heat of hydration (Larrard and Malier, 1999), which is not favourable to foamed concrete as it can lead to significant core temperature rises and can have adverse effect (Jones and McCarthy, 2006).

2.4.1.5 Metakaolin

Metakaolin (MK) is a pozzolanic material which is highly active and effective pozzolan for the partial replacement of cement in concrete. It is an ultra-fine material, with specific surface area of metakaolin, in the range of 4000m^2/kg to 12000m^2/kg (Neville, 1996). MK is obtained by the calcinations of kaolinitic clay at a temperature ranging between 500°C and 800°C. On reaction with $Ca(OH)_2$, MK produces CSH gel at ambient temperature and reacts with CH to produce alumina containing phases (Siddique and Klaus, 2009). The inclusion of metakaolin in concrete improved several mechanical properties of concrete such as increased compressive and flexural strengths, reduced permeability, increased resistance to chemical attack, increased durability, reduced effects of alkali-silica reactivity (ASR), reduced shrinkage, enhanced workability and finishing of concrete (Siddique and Klaus, 2009). Even though metakaolin has the potential to improve the performance and enhance the durability of concrete, its use in tests and applications are limited because of its high cost (Bai and Wild, 2002). The incorporation of metakaolin, up to 25% in blended cements, has shown pore refinement to 63% of the original pore size (Frı´as, 2006). No literature has been published on the use of metakaolin in foamed concrete, although it has been noted that the use of metakaolin was possible to increase the strength of foamed concrete (Jones, 2000). In the study of rheology, microstructure and instability in foamed concrete, metakaolin was used as replacement of cement to a level of 20%.

2.4.1.6 Calcium sulphoaluminate cements

Calcium sulphoaluminate cements (CSA), known as the 'third cement series' are rapid-hardening, high strength, expansive, or self-stressing cements. They were intended to manufacture self-stress concrete pipes because it has swelling properties (Pe´ra and Ambroise, 2003). They originated from China and have been used as binder for concrete in bridges, leakage and seepage prevention projects, concrete pipes, precast and prestressed concrete elements, waterproof layers, glass fiber reinforced cement products, low temperature construction and shotcrete. The alkalinity of CSA cements is about 1 pH unit lower than for Portland Cement, which decreases protection from corrosion of steel reinforcement and alkali aggregate reaction (Juenger et al., 2010). The durability of building materials made from CSA cements was found to be comparable to conventional Portland cement-based materials, although more studies are required for the long-term behaviour (Juenger et al., 2010). Carbonation was found to be more rapid in CSA cements compared to Portland Cement concretes, leading to the decomposition of ettringite which led to moderate strength loss. CSA cements are significantly greener compared to Portland Cement. It releases less than half of the CO_2 per g of cementing phase compared to Portland Cement. The firing temperature used to produce CSA clinker is about 200°C lower than that used for Portland cement clinker (Juenger et al., 2010).

Cement alone is not the only factor governing the efficacy of foamed concrete. Whilst strength is a vital factor in normal concrete, this is not the case in foamed concrete. With its own unique set of characteristics and behaviour, foamed concrete should be regarded as a materials group in its own right (Jones and McCarthy, 2005b). It is noted that different cement content and cement combinations had affected the temperature profiles, foam and mix stability (Jones and McCarthy, 2006).

2.4.2 Water

The role of water in concrete is well-documented. A brief review of this role is helpful in understanding the importance of water in foamed concrete. In the production of concrete, water is essential to precipitate chemical reaction with the cement, to wet the aggregate and to lubricate the mixture for easy workability (Nawy, 2001). The chemical reaction between cement and water produces the character of the colloidal gel or cement, hence, the proportion of water to the cement is of more concern and not the proportion of water relative to the whole mixture of dry materials.

The quantity of water in a mix is usually expressed either as litres/cubic metre or as a water-cement (w/c) ratio by weight. The 'free' water is the amount after allowance has been made for actual or potential absorption by the aggregate of which only a part is required for reaction with the cement, while the rest is present simply to make the mix sufficiently workable for the intended use (Tattersall, 1991).

Mixing water should conform to BS EN 1008 Mixing water for concrete. This standard includes potable water and establishes the suitability of water that is recovered or reclaimed from processes in the concrete industry or where water from non-mains sources, such as boreholes, is in use. Highways Agency and TRL (2001) noted that in foamed concrete it is crucial to use potable water when using a protein-based foaming agent because organic contamination can have an adverse effect on the quality of the foam, and hence the concrete produced.

Several studies have shown the effect of water on some properties of foamed concrete is not similar to the effects in normal concrete. Dransfield (2000) found that strength increased with increasing w/c ratio and with increased workability. He suggested that w/c ratio plays a smaller part in the strength of foamed concrete. In contrast, other researchers found that the w/c ratio is a significant factor in foamed concrete; too little water potentially leads to disintegration, too much water leads to segregation. Kearsley (1999), Highways Agency and TRL, (2001) and Nambiar and Ramamurthy (2006b) are in agreement that when there is too little water, water is withdrawn from the foam and the foam degenerates rapidly. Since density of foamed concrete is a function of the percentage foam added to the mixture, this will cause a variation in the density. Conversely, these authors also noted that, when there is too much water, segregation will take place.

In addition, in this context of high w/c ratio, Highways Agency and TRL, (2001) suggested that water-cement ratio of the base mix required to achieve adequate workability is dependent upon the type of binder(s), the required strength of the concrete and whether or not a water-reducing or plasticizing agent has been used.

2.4.3 Fillers

2.4.3.1 Fine aggregates

Only fine aggregate or sands with particle size of up to 5.0 mm in excess of 50% passing 600 μm sieve are used (BCA, 1991) since coarser aggregates may settle in the lightweight grout and cause collapse of the foam during mixing (BCA, 1991). However, fine sand is practically restricted to mixes with densities above 1200 kg/m^{3,} below which the fillers must be partially or totally replaced with other fillers such as coarse fly ash (Dransfield, 2000).

2.4.3.2 Coarse fly ash

Coarse fly ash (conforming to BS 3892: part 2:1997 or BS EN 450: 1995) can be used as a partial or total replacement for sand to produce foamed concrete with a dry density below 1400 kg/m^3 (Highways Agency and TRL, 2001). Foamed concrete mixes using coarse fly ash exhibited enhanced consistency and rheology compared to sand concretes and improved longer-term compressive strength (Jones and McCarthy, 2005b). However, the fly ash mixes required up to three times more foam than the calculated quantity to achieve target plastic density, which was probably due to foam instability. They suggested that the instability was possibly due to the highly fluid consistency of the base mix and the adverse effects of the highly residual carbon in the ash. In his study, Nambiar and Ramamurthy (2006b) found similar results using coarse fly ash.

2.4.3.3 Other aggregates

Replacement of sand/fine aggregate by demolition fines or conditioned fly ash has a beneficial effect on a wide range of foamed concrete properties, which is a major breakthrough in potentially saving aggregate materials for construction purposes (BRE, 2004, Yerramala, 2008 and Rao, 2008).

Highways Agency and TRL (2001) stated that limestone fines up to 10 per cent by weight of cement were added in conjunction with fly ash to accelerate the setting rate of foamed concrete. Other aggregates include lightweight aggregates up to 16mm in size, such as expanded polystyrene granules and Leca expanded. Any such aggregates should be about the same density as foamed concrete and have minimal capacity for absorbing water.

Other fillers such as chalk, crushed concrete (Aldridge, 2005), crushed dust, expanded polystyrene granules, Lytag fines (Dijk, 1991), polystyrene beads (Cox, 2005) and granite dust (BCA, 1991) had been found to be used as fillers in foamed concrete. For the purpose of the current study, the main fillers used are fine aggregates (sand) and coarse fly ash, as these are the common fillers used in construction. Demolition fines were also briefly included in the study of stability as comparison to main fillers.

2.4.4 Foam

A significant characteristic of foamed concrete is the ability to control its density over a wide range, and this is achievable by adding a calculated amount of foam to the base mix (Wee et al., 2006). There are two methods of introducing foams in foamed concrete production; by adding preformed foam or by mixing the mortar with foaming agent such as detergents, resin soap, glue resins, saponin, and hydrolysed proteins. The most common type is the use of preformed foam as it is reported to be the most economical and controllable pore-forming process and there are no chemical reactions involved (Nambiar and Ramamurthy, 2000b; Wee et al., 2006). Preformed foam comprises an aqueous foaming agent and air. The foaming agent is important as it gives the foamed concrete its final properties. If the foaming agent collapses, the mix may collapse leaving a very dense base mix.

The properties and quality of foam added to produce foamed concrete are critical, particularly when the foam comprises more than 50% of the foam and base material blend, which occurs at densities at or below 1100 kg/m^3 (Aldridge, 2005). The quality of the foam is affected by its density, the dilution factor of the agent, the foam-making process and the adding and blending process with the mortar. The foam must be capable of remaining stable and not collapsing during pumping, placement and curing (Dijk, 1991).

Preformed foam is divided into two categories; wet foam and dry foam. Wet foam is produced by spraying a solution of foaming agent and water over a fine mesh while dry foam is produced by forcing a similar solution of foaming agent and water through a series of high-density restrictions, combined with forced compressed air into a mixing chamber. The wet foam is slightly larger in size, loose and of size range of 2-5 mm in diameter. The dry foam is more stable, smaller at less than 1mm in diameter, thick, tight and similar to appearance of shaving foam. The choice of foam depends on the application of foamed concrete (Aldridge, 2005).

2.4.4.1 Foaming agents (Surfactants)

Surfactants are wetting agents that lower the interfacial tension between two liquids and also lower the surface tension of liquid, allowing easier spreading. They contain both hydrophilic (water loving) and hydrophobic (water fearing) components at the molecular level. This promotes emulsion formation and enables the surfactant to reduce interfacial tension between two liquids by adsorbing at their interface. The term 'interface' indicates a boundary between any two immiscible phases; the term 'surface' denotes an interface where one phase is a gas, usually air (Rosen, 2004).

Synthetic or protein-based surfactants can be used to produce foam (BCA, 1994) and are formulated to produce air bubbles that are stable and able to resist the physical and chemical forces imposed in the process of making foamed concrete. The surfactant solution consists of one part surfactant and between 5 to 20 parts water (BCA, 1994). The concentration should be chosen with regard to its critical micelle concentration (CMC). CMC is a value where the surface tension stays constant after more surfactant is added, as shown in Figure 2.1.

Protein-based surfactants were the original surfactants. They were relatively crude materials derived from hydrolysed animal carcass residues which were subjected to biodegradation. However, the protein-based surfactants have been developed to be highly refined and stabilised. The foam produced is strong, closed cell, stable and has a strong firm texture which blends easily into mortar with little breakdown. Other properties include lower expansion ratio to solution volume to foam volume, sensitive to the alkalinity of the mix and blends easily into the mortar with little breakdown (Dransfield, 2000). Protein-based surfactants produce foamed concrete with strength/density ratio of about 50% to 100% higher compared to synthetic surfactants (McGovern, 2000). Additionally, it was noted that these add water repellent properties to the foamed concrete (Dijk, 1991).

A synthetic surfactant can be classified by the presence of charged groups in its head. The head of an ionic surfactant carries a net charge. Anionic is the group in which the charge is negative. This characterises about 70 percent of the surfactants used to produce foamed concrete. Cationic is the group of which the charge is positive. Cationic makes up less than 5 per cent of the surfactants used to produce foamed concrete. A non-ionic surfactant has no charge groups in its head and makes up 25 per cent of surfactants used to produce foamed concrete. The lack of electric charge may give a greater stability to the foamed concrete mix. The group of surfactant with heads of two oppositely-charged groups are termed amphoteric or zwitterionic. Their molecules can sustain either a positive or negative charge, or both charges, depending on the pH of the solution. They are rarely used to produce foamed concrete (Myers, 1992).

Dransfield (2000) stated that synthetic surfactants are stable, easy to formulate and consistent in performance. However, the bubble size is larger and the cells are more open due to higher expansion. These results in foamed concrete of lower strengths compared to foamed concrete produced using protein-based surfactants.

As noted by the Highway Agency and TRL (2001), at present, the effect of the nature of the surfactant on the properties of the foamed concrete is largely unknown. Selections of surfactants are based on an empirical basis as the performance of the various types of surfactant varies with the type of binder. In this study, commercially available synthetic and protein surfactants are investigated.

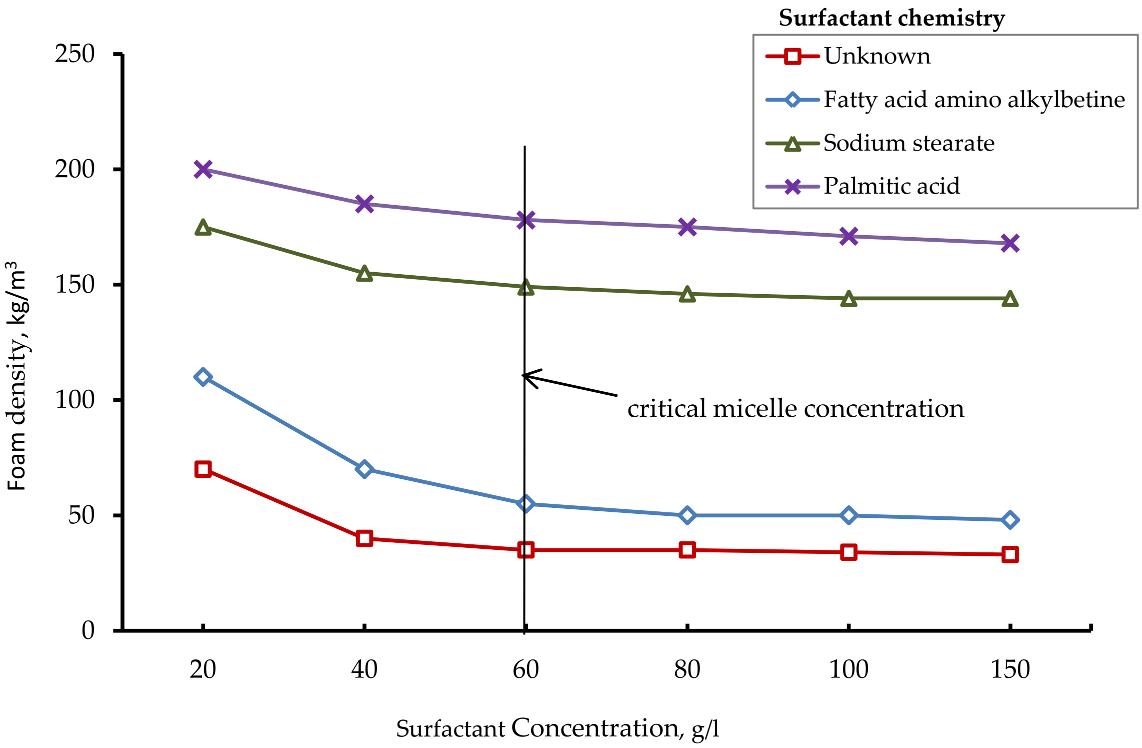


Figure 2.1: Critical micelle concentration of different surfactant types (Dhir et al. 1999)

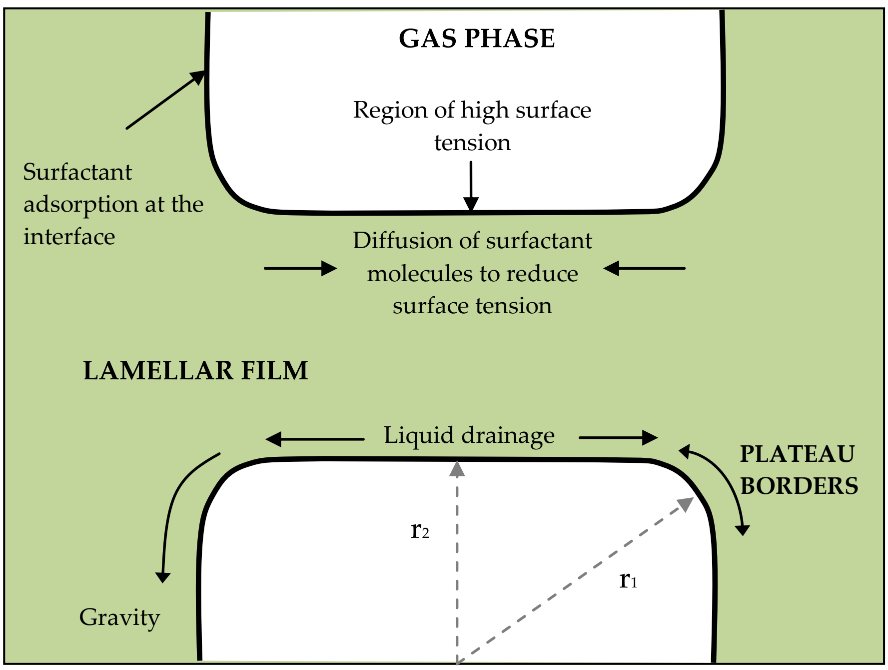


Figure 2.2: Schematic effect of dynamic equilibrium state (Gibbs – Marangoni effect) of foams (Myers, 1992)

2.4.4.2 Foam Stability

When bubbles form, pressure and surface tension differentials occur at two distinct areas of the bubbles. At the Plateau border, there is lower surface tension compared to that at the lamellar film, where there is a higher surface tension, as shown in schematically in Figure 2.2.

At the gas-liquid interface, the pressure difference (ΔP) and the surface tension (γ) acting upon an element of the surface is expressed according to Laplace law:

$$\Delta P = \gamma \; (1/r_1 + 1/r_2) \qquad \textit{Equation 2.1}$$

where,

ΔP = pressure difference across a curved interface due to the surface tension of the solution.

γ = surface tension of the solution

r_1, r_2 = principal radii of curvature of the surface (Plateau borders and less curved regions in the lamella)

The differences in curvature (r_1, r_2) cause fluid drainage from the lamellar regions to the Plateau borders to restore the imbalance in liquid pressure. Additionally, liquid drainage from the lamellae also occurs because of gravitational forces. Liquid drainage by gravity is important in thick lamella, when the foam is first formed, while drainage by surface tension occurs when the lamellae are thin. These factors resulted in the thinning of the film. Two theories which explained this effect are known as the Gibbs effect and the Marangoni effect (Rosen, 2004). The Gibbs effect is based on the theory that the change in surface tension corresponds to the change in concentration of the surface active solutions. Alternatively, the Marangoni effect is based on the theory that the diffusion of surfactant molecules from the Plateau border to the lamellar film occurs to oppose film thinning. Both theories postulate that these occurrences continue until a critical film thickness is achieved at 50 – 100Å where the film ruptures spontaneously, when it is unable to withstand the exerted pressure.

2.5 MIX PROPORTIONS

There is no standard method for designing foamed concrete mix (Highway Agency and TRL, 2001). Furthermore, the method used for designing normal concrete mix compositions cannot be used for designing foamed concrete mix compositions. For normal concrete, the compressive strength determines the water/cement ratio in order to calculate the volume of water required. By contrast, in foamed concrete, the target density and water/cement ratio are the determining factors (Kearsley and Mostert, 2005a). The mass of the cement and the volume of foam can be calculated using these target values and can take into account the densities of the constituent materials. Basically, for a target plastic density (D, kg/m^3) and water/cement ratio (w/c), the cement content (c, kg/m^3), the total mix water (W, kg/m^3) and fine aggregate content (f, kg/m^3) are calculated from equations as follows:

Target plastic density, $D = c + W + f$ *Equation 2.2*

where c = cement content, f = fine aggregate and free water content, W= (w/c) x c

Additionally, the air-void characteristics plus the curing regime determines the strength of foamed concrete. The air-void characteristic is determined by the type of foam used, and is governed by the type of foaming agent (Aldridge, 2005). As noted, both synthetic and protein surfactants produced different qualities of foam, resulting in different characteristics of foamed concrete. Since there is a wide range of surfactants available, the selection of suitable surfactants depends on the particular application (Highway Agency and TRL, 2001). Synthetic surfactants give a higher expansion, produce foamed concrete of lower strengths compared to protein surfactants and generally work at lower concentrations (Dransfield, 2000). In contrast, the smaller size and more stable bubbles from protein-based surfactants produce foamed concrete of relatively high density and high strength (Highway Agency and TRL, 2001).

Dransfield (2000) stated that the role of w/c ratio in foamed concrete is relatively minor and that strength may actually increase with increasing w/c ratio and with increased workability. However, the Highway Agency and TRL (2001) reported that reduced water/cement ratio caused an increase in strength of the foamed concrete but at the expense of reduced workability. As a result of low workability, there is an increased foam breakdown during mixing (Dransfield, 2000) and the collapse of the foam will alter the final w/c ratio rather than the calculated mix proportion (Highway Agency and TRL, 2001).

The calculation of the mix design is further complicated when using other materials such as fine fly ash, FA_f (replacing part of cement) and/or coarse fly ash FA_c(replacing part of sand) as this alters the amount of water required (Kearsley and Mostert, 2005a; Jones and McCarthy, 2005a).

2.6 MIXING PROCESS

The mixing process has a significant influence on foamed concrete. Within this process a single factor or a combination of factors can affect the quality of foamed concrete, such as the type of mixer, the speed of rotation and the mixing time. The mixer type is responsible for uniform distribution of preformed foam (McCarthy, 2005). The most successful type has a folding action where paddles rotate on a horizontal shaft or a screw action in a trough (Dransfield, 2000 and Jones, 2000). By contrast, pan mixers cause the preformed foam to sit on the mortar surface instead of being folded in; rotating mixers have no folding action and rely on free-falling action (Dransfield, 2000). Additionally, the rotating mixers do not provide enough shear to produce sufficient base-mix workability (Jones, 2000). The speed of rotation, such as in a ready-mixed truck, affects the foam dosage required (Highway Agency and TRL, 2001). Short mixing times were said to produce inhomogeneous foamed concrete, while prolonged mixing at high speeds leads to disintegration of the foam (Kearsley, 1999). However, Beningfield et al. (2005) asserted that there is no evidence to prove that prolonged mixing produces excessive air or causes air loss.

The process of blending foam with the base mix can be carried out in ready-mixed trucks, either at the plant or on site (Aldridge, 2005). There are two basic methods of producing foamed concrete; the preformed foam method and the inline method. With the preformed foam method, the base materials are delivered to the site in a ready-mixed truck and preformed foam is injected directly into the back of the ready-mixed truck whilst the drum is on fast spin. The volume and quality of the foamed concrete is determined by the capacity of the ready-mixed delivery truck.

The other method of site mixing is the inline system which has two types: the wet method inline system and the dry method inline system. In the wet method, the dry base materials and the foam are fed through a series of static inline mixers where the two components are mixed together. As illustrated schematically in Figure 2.3, the foam can be added through foam injection into the truck mixer, a special blender or into a flexible hose (Dijk, 1991). These mixers have the effect of blending the foam and the base materials together into a completely homogenized mix ensuring a completely repeatable process. For control purposes, the density is constantly checked via the continual on-board density monitor. The output volume is not governed by the size of the truck, which makes this process an effective method of working on site (Aldridge, 2005).

The dry method inline system operates on a similar principle except that the dry materials are loaded in silos which can be weighed and batched on site (Aldridge, 2005; Cox and Dijk, 2002). Once blended, the base mix is then pumped to a mixing chamber where foam is added. This system is ideal in areas where base materials are difficult to obtain. However, the disadvantage is that it requires a large amount of water on site to create the mix, which is undesirable for congested city centres or project sites where water cannot be supplied easily (Aldridge, 2005).

2.7 CURING

The need for curing concrete has been recognized since the inception of concrete. Although methods of curing for conventional concretes have been established, the curing regimes for foamed concrete are still being explored. Kearsley (1996 and 1999) studied conventional water curing, sealed curing and air curing at different temperatures, moist curing, steam curing at atmospheric pressure and high pressure steam curing (also called autoclaving). She concluded that water-cured foamed concrete exhibited lower apparent strengths and the highest strengths were obtained on specimens cured at 50^0C and on specimens sealed in plastic bags and held at a constant temperature of 22^0C. Increased temperature curing produced higher compressive strengths but is not regarded as cost-effective (Kearsley, 1999). After reviewing these varieties of curing, it was decided to adopt sealed curing in which the sample is wrapped in cling film and stored in plastic bags at constant temperature of 22^0C. This curing regime one of the most common regimes adopted by other researchers (Jones and

McCarthy, 2004, 2005a, 2005b, Kearsley and Wainwright, 2000a, 2000b, 2001a, 2001b, Wee et al., 2006)

2.8 DENSITY

The importance of the density of foamed concrete is well documented (Jones et al., 2003; Jones and McCarthy, 2006; Nambiar and Ramamurthy, 2006b). The ability to control its density is one of the main advantages of foamed concrete. The designed densities which are within the range of 300 to 1600 kg/m^3 have a strong influence on the properties of the foamed concrete. Although there is no standard method for proportioning foamed concrete, the general rules regarding w/c ratio, free water content and maintaining a unit volume is for a specified target plastic density that becomes a prime design criterion (Jones and McCarthy, 2006).

It is difficult to design for a specific dry density, as foamed concrete will desorp between 50 and 200 kg/m^3 of the total mix water, depending on the concrete plastic. A tolerance on plastic density is usually acceptable to ± 50 kg/m^3 of the target value, which is typical of industry practice for foamed concrete production (Jones and McCarthy, 2006).

Instability in foamed concrete causes the densities to vary and this may cause segregation, unpredictability, collapse and eventually unfitness for purpose. Increased density after solidification may occur due to the collapse of bubbles. However, foamed concrete made with protein surfactants is said to have same the densities both when freshly mixed and after 24 hours (Yerramala, 2008).

A variation in design density ratio (measured fresh density divided by design density) with water-solids ratio for mixes with different filler type for 1000 kg/m^3 is shown in Figure 2.4 (Nambiar and Ramamurthy, 2006b). The density ratio shown is higher than unity at lower consistence. Nambiar and Ramamurthy (2006b) suggested that the mix was too stiff to mix properly thus causing the bubbles to break during mixing and this resulted in increased measured density. Conversely, in the same study, at higher water-solids ratio, higher water content made the slurry too thin to hold the bubbles. This caused segregation of the foam from the mix, hence segregation of the mix itself, which resulted in an increase in measured density.

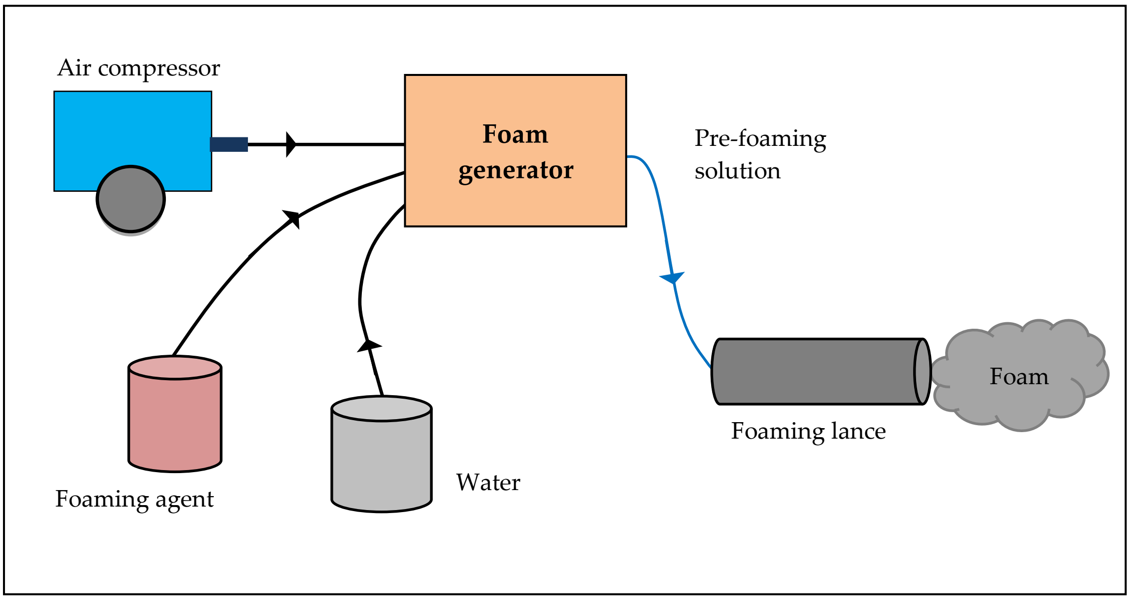


Figure 2.3: Schematic diagram of the production of foam for foamed concrete

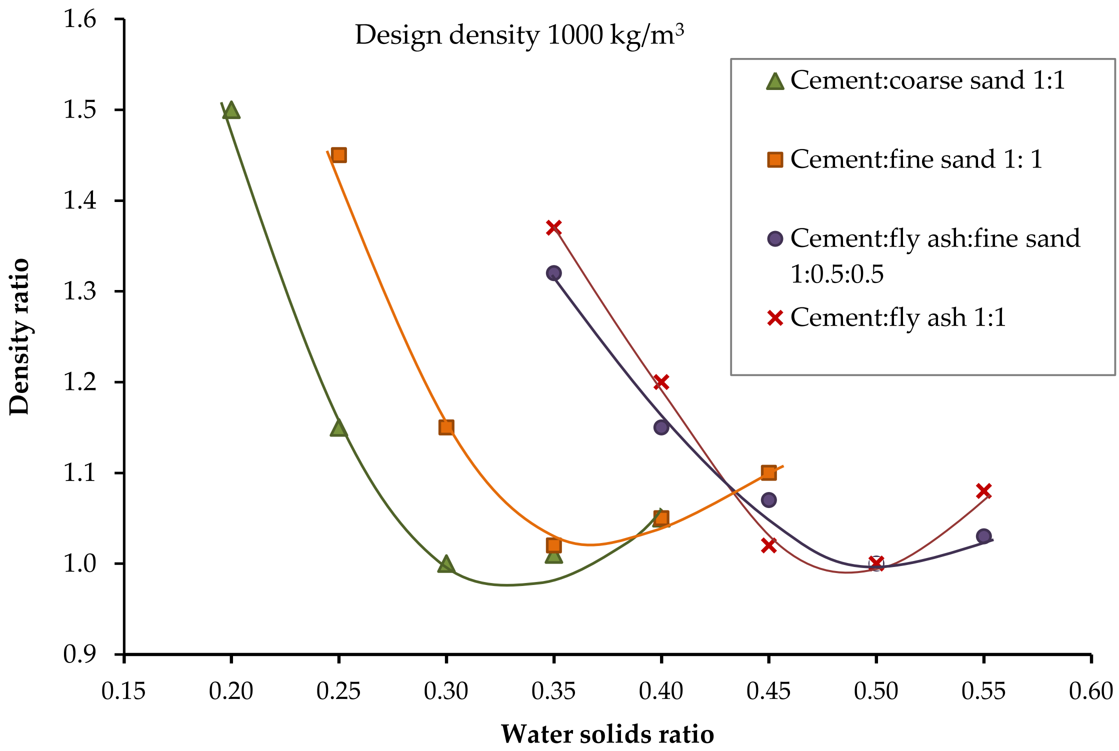


Figure 2.4: Variation of density ratio with water–solids ratio for different filler type (Nambiar and Ramamurthy, 2006b)

2.9 PROPERTIES OF FOAMED CONCRETE

The properties of foamed concrete are diverse, ranging from fresh state properties, early age properties to hardened state properties. For the purpose of the current study and this literature review in particular, discussion will be confined to three significant properties, namely, workability in the fresh state, rate of hardening and instability in the early age stage. Of the range of properties in the hardened state, discussion will be confined to compressive strength, modulus of elasticity and microstructure. In addition, other related properties will also be cited in this review.

2.9.1 Fresh State Properties

The fresh state of all cement–based materials may be only transient, but it is of major importance to the ultimate performance in the hardened properties (Banfill, 2003, Hanehara and Yamada, 2008). However, in most reported research, the fresh state of cement-based materials is usually described by its characteristics.

Generally, the properties of foamed concrete are described as free-flowing, self-levelling and self- compacting (Dransfield, 2000; Jones et al., 2003; Jones and McCarthy, 2005a, 2005b, 2005c, 2006). In basic terms, the workability of foamed concrete containing relatively large amounts of air pores is generally excellent; it has nearly fluid consistency, is easily pourable, homogeneous and small possibility of bleeding and segregation. Additionally, foamed concrete is readily placed without need of further consolidation (Basiurski, 2000).

The term 'workability', as commonly described in normal concrete, is limited in definition and methods of measurement; however, the principles of rheology are more for describing the behaviour of fresh concrete (Domone, 2003).

For this reason, the fresh state of foamed concrete is clarified in terms of workability (as universally described in all cement–based materials) and of the use of rheological properties as described by researchers such Jones et al., (2003), Jones and McCarthy (2005a; 2005b) and Highways agency and TRL (2001). Whilst many studies have been conducted on rheology of cement-based materials (Tattersall, 1991; Domone, 2003; Banfill, 2003; Lachemi et al., 2007; Roussel, 2007), to date, the literature on the rheology of foamed concrete is very limited.

2.9.1.1 Rheology

Rheology, the science of the deformation and flow of matter, is concerned with the relationships between stress, strain, rate of strain and time. As the rheology of cementitious material is closely related with developing performance of concrete, the rheology is considered one of the most important factors for all cement–based materials (Banfill, 2003). Rheology is important in understanding how cement paste, grout, mortar and concrete perform in practical applications and the scope it offers for characterising their properties (Banfill, 2003).

Paste, mortar and concrete are considered as non-Newtonian fluid, of which, the viscosity changes with the applied strain rate. The most commonly used model for the prediction of these cementitious material is the Bingham model, which requires two important parameters, namely, yield stress τ_0 and plastic viscosity η. Bingham fluid follows the equation:

$$\tau = \tau_0 + \eta\,\gamma\,; \qquad \textit{Equation 2.3}$$

where τ is the shear stress (N/m^2) at the shear strain rate γ (rev/sec). τ_0 is the yield stress (N/m^2) and η is the plastic viscosity (Ns/m^2). The yield stress is the stress above which the material becomes fluid and starts to flow and is associated with filling capacity and ability to flow under applied stress, as shown in Figure 2.5. Plastic viscosity, η is the measure of how easily the material flows, once the yield stress is overcome. Plastic viscosity is associated with the velocity at which a given concrete will flow, once flow is initiated (Roussel, 2007). Lower yield stress gives less resistance to start the flow of concrete. Higher viscosity prevents segregation, but provides high resistance to the flow of concrete.

Foamed concrete behaves like a non-Newtonian which follows the Bingham model. In basic terms, the workability of foamed concrete containing relatively large amounts of air pores is generally excellent - easily pourable, nearly fluid consistency, homogeneous and without possibility of bleeding and segregation and readily placed without need of further consolidation (Basiurski, 2000). Foamed concrete has the tendency to manifest reduced self-levelling in the very low density range, because of the reduced dead weight and the increased cohesion of the concrete arising from the high volume of air (Nambiar and Ramamurthy, 2006b). This statement confirms an earlier study by Jones and McCarthy (2005a) who found that lower density foamed concrete exhibited highest apparent yield stress which they claimed could be attributed to the reduced self-weight, higher air content and lower water content. They also found that, within the range of densities studied (1000-1400 kg/m^3), the plastic viscosities of the foamed concrete were small. However, foamed concretes with sand exhibited higher yield values than foamed concretes with fly ash at higher densities (1400-1800 kg/m^3). This was attributed to much larger and more angular shaped sand particles with smaller surface area.

Jones and McCarthy (2005a) stated that yield values of foamed concrete are typically less than 2 Nm, which is indicative of self-flowing behaviour. Replacing sand with coarse fly ash reduced the yield value, as shown in Table 2.2 (McCarthy, 2004). With increased plastic density, this effect is increased. However, in plastic viscosity, the decrease is smaller with increased plastic density. The yield values were obtained by plotting speed, (rev/sec) against torque (Tattersall, 1991)

Therefore, reducing the filler mean size particle greatly reduces the yield stress necessary to get the mix flowing and produces a more fluid concrete due to rounded particle morphology (McCarthy, 2004). This permits effective particle packing, reducing water demand without decreasing fluidity of the mix (Nonat and Mutin, 1991). Additionally, they noted that fly ash particles are less reactive than cement; hence the retardation effect of fly ash results in decreased viscosity and yield stress of fly ash cement.

All these basic knowledge of rheological behaviour of foamed concrete will be further investigated in this study that will include the effect of different types of surfactants to the rheological properties.

2.9.1.2 Rate of hardening

There is no standard method for determining the initial and final setting times of foamed concrete, although the methods given in BS 4550:1978 and ASTM C266-89 for cements provided the basis of suitable methods for the preparation of foamed concrete (Highways and TRL Agency, 2001).

In previous studies, stiffening for all foamed concrete mixes did not appear to take place until 5 hours after casting at 20^0C (Dhir et al., 1999). As shown in Figure 2.6, all foamed concrete mixes achieved the set limits given in BS 4550: 1978 up to 9 to 10 hours. The 'setting' time of foamed concrete is usually between 12 and 24 hours. The amount of foam incorporated into the mix has an effect on the stiffening time of foamed concrete since foaming agents have chemical similarities to retarding admixtures. Consequently, the stiffening time is inversely proportional to foamed concrete density (Jones, 2000).

The average setting time of foamed concrete with a 1-day strength of 1.0 N/mm^2 was between 12 and 24 hours, although this could be improved with rapid hardening cement types, insulating formwork, raising the ambient temperature or using accelerators (Dijk, 1991). Accelerators can be used to increase the slow rate of stiffening and strength development of foamed concrete. Since the mechanism for accelerated curing is not fully understood, its use can be recommended only on empirical basis. Calcium chloride is regarded as the most effective accelerator which can be used in most conditions in foamed concrete because carbon steel reinforcement is rarely used with foamed concrete, unlike typical reinforced concrete (Dransfield, 2000).

Table 2.2: Typical rheology of sand and fine fly ash, FA_f aggregate mixes, from Dhir et al. (1999)

Plastic density kg/m^3	Yield Value, Nm*			Plastic Viscosity, Ns/m^2		
	Sand	FA	Decrease,%	Sand	FA	Decrease, %
1400	0.82	0.44	46	0.034	0.025	26
1600	1.13	0.52	54	0.040	0.032	20
1800	1.80	0.69	62	0.051	0.045	12

1. Assessed using Brookfield RVT Viscometer
2. Nm* is the yield value obtained from plotting graph speed (rev/sec) against torque (N/m)

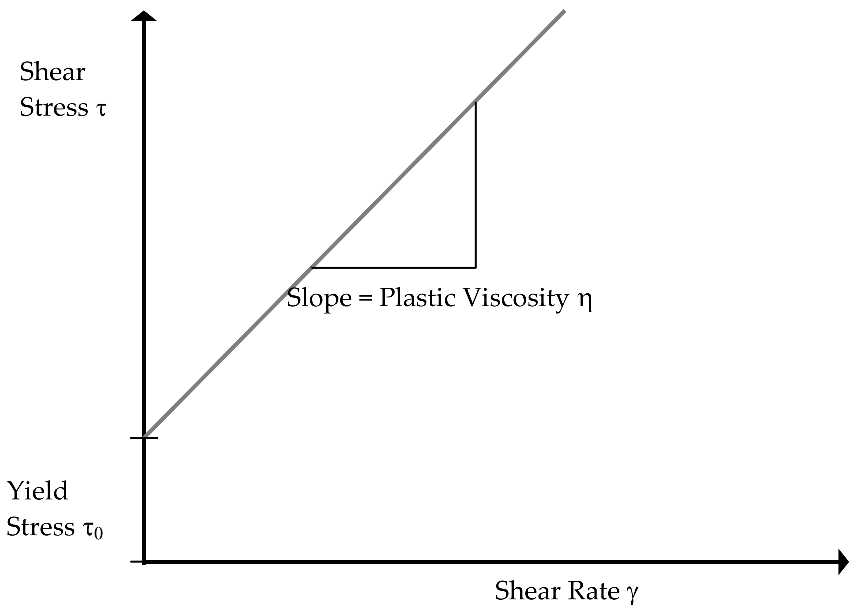


Figure 2.5: Bingham model $\tau = \tau_0 + \eta\, \gamma$

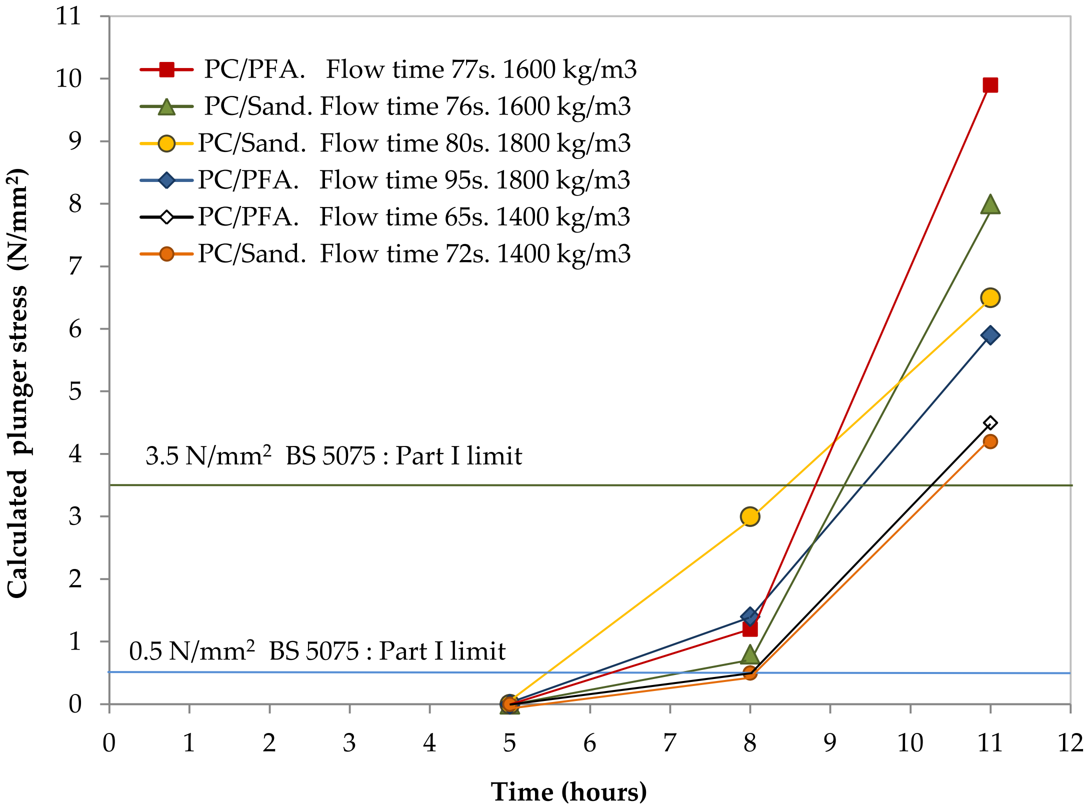


Figure 2.6: Comparison of stiffening times of various foamed concrete (Jones, 2001)

2.9.1.3 Stability

In order to understand the importance of stability in relation to other properties of foamed concrete, it is imperative to define stability. Stability is one of the variables of the definitions of workability and consistency in normal concrete. Stability is cited as the ability to resist segregation, a condition which refers to the cohesion of the mix and rarely used as an objective and quantifiable description of a concrete mix (Neville, 1996). In self-consolidating concrete, which is highly flowable and contains relatively low content of cementitious materials, stability is essential to ensure an adequate air void system (Khayat and Assaad, 2002). The air void system has to remain stable during agitation, placement and setting.

Stability in foamed concrete had been described for fresh state conditions of two materials; preformed foam and foamed concrete (Aldridge, 2001, 2005; McGovern, 2001; McCarthy, 2004; Jones and McCarthy, 2006; Nambiar and Ramamurthy, 2007a, 2007b, 2008). The inclusion of foam in foamed concrete raises the expectation that the stability of the foam will have a strong influence on the latter, particularly when the volume of foam to base mix becomes greater than 50% (Aldridge, 2005). Larger bubble size and more open cells which are characteristics of foams produced by synthetic surfactants, are said to be less stable compared to foams produced from protein-based surfactants (McCarthy, 2004). Additionally, the stability of the foam was found to be affected by surface charges, 'free' water content, fly ash and chemical admixtures (Jones and McCarthy, 2006).

Jones and McCarthy (2006) conducted a study that suggested that the stability of foamed concrete can be assessed by comparing the calculated and actual quantities of foam required to achieve a plastic density and by visual observation. In their study incorporating fly ash in foamed concrete mixes, the foam stability was found to be affected by the high fly ash content which had caused the foam to collapse. This resulted in additional 'free water' which, in turn, required higher foam volume to achieve the target plastic density. By contrast, Nambiar and Ramamurthy (2007b) initially defined stability of foamed concrete mix as the state of condition at which measured density is equal to or nearly equal to design density. In a later study, Nambiar and Ramamurthy (2008) defined stability of foamed concrete as 'the state of the mix at which the density ratio is closer to unity'. They affirmed that the stability of foamed concrete depends on three factors: the foam volume, consistency of the base mix and filler type.

Whilst appreciating the variety of definitions of stability in foamed concrete, earlier definitions had been descriptive of the fresh state properties of both, preformed foam and foamed concrete. However, in this current study, stability is identified as a characteristic of early age properties of foamed concrete. This feature may be akin to the stability found in normal concrete explained by Neville (1995) as cohesion of the mix, that is, resistance to segregation that has meaning only under a given set of circumstances (Neville, 1995).

The ideal mix design of any fluid concrete is located somewhere between being fluid enough to flow and fill to having acceptable stability to resist segregation and deformations (Roussel, 2007). This is comparable to foamed concrete, where, in most applications it is expected to flow and self level. Investigations into the properties of foamed concrete have been based on assumptions in primary studies when its stability has not been called into question. The literature reflects an assumption that foamed concrete stability is beyond doubt. For example, it had been stated that foamed concrete is said to exhibit stable consistency with low plastic shrinkage (Technology Bulletin, University of Dundee: Issue 13, 2007) and one of the advantages of using foamed concrete is that foamed concrete does not collapse after placement as it sets (Basiurski, 2001). However, only passing references to stability have been made, little attention has been paid to exploring the validity of assumptions about stability. Research has been incomplete in this respect.

In preliminary work, concerns have been expressed about instability in foamed concrete. Bennett (2002) suggested the water: cement (w/c) ratio of the base mix should be kept fairly high to avoid water being extracted from the foam thus causing it to collapse. Jones et.al (2005c) noted foam collapse during mixing and transporting although the degree of collapse is unpredictable and varies with mix constituents. Segregation is often checked as measure of instability (Dransfield, 2000; Jones and McCarthy, 2006).

The paucity of literature in this area reinforces the lack of concern about stability in the past. In one recent study, Nambiar and Ramamurthy (2008) found that stability of foamed concrete is affected by the water content in the base mix, the amount of foam added and other solid ingredients in the mix. Although this single piece of research has examined the constituent materials, in order to expand our understanding of the behaviour of foamed concrete, it is necessary to consider other possible factors that affect the stability.

The purpose of the present study is to examine the nature, structure and production of foamed concrete in an attempt to identify causal factors that give rise to potential instability in foamed concrete. Additionally, this study examines the relationship of stability with other properties namely, rheology and microstructure.

2.9.2 Hardened State Properties

2.9.2.1 Compressive Strength

In the past, strength was not the main issue when using foamed concrete (Dransfield, 2000; Beningfield, 2005) as it was typically used in void filling, highway reinstatement and other underground works. The typical strength value for foamed concrete of densities between 800 – 1000 kg/m^3 is between 1 – 8 N/mm^2 (BCA, 1994; Dransfield, 2000) which was sufficient for its purpose in underground works. With a minimum strength of 25 N/mm^2, foamed concrete has the potential to be used as a structural material (Jones and McCarthy, 2005b). Based on this objective, several research projects were undertaken to study the possibility of increasing compressive strengths (Kearsley, 1999; Jones and McCarthy, 2005b; Nambiar and Ramamurthy, 2006b). The summary of properties of foamed concrete indicating the typical compressive strength as defined by BCA (1994) is shown in Table 2.3.

The compressive strength of foamed concrete is affected by the density, cement type and content, water/cement ratio, surfactant type and curing regime (Jones and McCarthy, 2005c). Density has been shown to be directly related to compressive strength, where increases in density resulted in increases in compressive strength (Kearsley, 1999; Jones, 2000; Nambiar and Ramamurthy, 2006b). As illustrated in Figure 2.7, this is explained by the greater air content in lower density which makes the foamed concrete weaker (Dhir et al. 1999). However, density is not directly reliable as an indicator of strength or quality, when constituents of the foamed concrete vary (Highway Agency and TRL, 2001).

Typically, as reported by Neville (1996) higher cement content resulted in increased strength of normal concrete. Similarly, in foamed concrete, Jones (2000) found that an increase in cement content increased the strength for a range of values although the strength increase was found to be minimal above cement content 500kg/m^3. Thus, owing to this minimal strength gain, adhering to an acceptable minimum cement content is both economical and practicable (Kearsley and Mostert, 2005a).

For a given density, different combinations of other cements and different cementitious fillers (coarse fly ash, conditioned fly ash, incinerator bottom ash, demolition fines, china clay, quarry fines and others) influenced the compressive strengths (Jones and McCarthy, 2005c). Keeping other factors constant, finer sand showed an increase in strength compared to coarser sand (Nambiar and Ramamurthy, 2006b), Figure 2.8. In Figure 2.9, Jones (2000) noted that when coarse fly ash was used as filler, the strength showed significant increase between 28 to 56 days compared to the strength achieved when sand was used in which case only a marginal increase in strength occurred after 28 days. In that particular study, it was observed that at any given density, the 28-day compressive strengths of fly ash foamed concretes were higher than sand foamed concretes. The difference was further increased after 56-days. Other researchers found similar trends when using fly ash as cement replacement and/or coarse fly ash as fillers (Jones and McCarthy, 2005a; Kearsley and Mostert, 2005a; Nambiar and Ramamurthy, 2006b). The effect of other cements such as ground granulated blast furnace and silica fume also influenced the compressive strengths and other properties of foamed concrete, for example, the consistency and stability (Highway Agency and TRL, 2001).

It is well established that in normal concrete decreases in w/c ratio cause significant increase in strength. However, this trend is not confirmed in foamed concrete in the current literature. Dransfield (2000) observed that w/c ratio was not only less significant, but that, the strength increased with increases in the w/c ratio. On the other hand, De Rose and Morris (1999) found that strength decreased with increasing w/c ratio up to 0.45, and noted that above this reading, the trend is reversed, that is, where the strength increased with an increase in the water/cement ratio.

The surfactant used is also important as it gives the foamed concrete its final properties (Aldridge, 2000). Protein-based surfactants produced more stable, smaller and stronger bubble structure, hence higher strength foamed concrete compared to synthetic surfactants which produces bigger bubbles (BCA, 1991; Aldridge, 2000; McGovern, 2000). This higher performance by protein surfactants can be attributed to the ability to take on water and hold it within the protein structure. This makes it somewhat absorbent which allows hydration process; hence cement particles are well-bonded around air bubbles. As a result, the mechanical strength of the air matrix is stronger (McGovern, 2000).

The curing regime has a significant effect on the strength of foamed concrete. In her study, Kearsley (1999) noted that highest strengths were obtained on specimens cured at 50^0C, then sealed in plastic bags, and kept at constant temperature of 22^0C. By contrast, she further showed that specimens that were water-cured gave low strengths which were probably due to build-up of pore water pressure in the saturated microstructure of the foamed concrete. Because of the variations, a curing regime must be established to maintain quality control. By the same note, the strength of foamed concrete cannot be equated with autoclaved aerated concrete. Although the latter results in higher strength, these results are controlled by the requirements of factory autoclaving (Jones and McCarthy, 2005). Furthermore, steam curing is used in the precast industry to obtain the highest possible strength at lowest density in the shortest time (Kearsley and Mostert, 2005). A summary of the effects of these parameters on the compressive strength are shown in Figure 2.10.

Although strength is not an issue in many applications of foamed concrete (Dransfield, 2000; Beningfield et al., 2005), it is a main characteristic which relates to other properties, hence the reason for the study of compressive strength in almost all research on foamed concrete.

Table 2.3: Summary of properties of hardened foamed concrete (BCA, 1994).

Dry density (kg/m³)	7-day compressive strength (N/mm²)	Thermal conductivity (W/mK)	Modulus of Elasticity (kN/mm²)	Drying Shrinkage (%)
400	0.5 – 1.0	0.1	0.8 – 1.0	0.30 – 0.35
600	1.0 – 1.5	0.11	1.0 – 1.5	0.22 – 0.25
800	1.5 – 2.0	0.17 – 0.23	2.0 – 2.5	0.20 – 0.22
1000	2.5 – 3.0	0.23 – 0.30	2.5 – 3.0	0.18 -0.15
1200	4.5 – 5.5	0.38 – 0.42	3.5 – 4.0	0.11 – 0.19
1400	6.0 – 8.0	0.50 – 0.55	5.0 – 6.0	0.09 – 0.07
1600	7.5 – 10.0	10.0 – 12.0	10.0 – 12.0	0.07 – 0.06

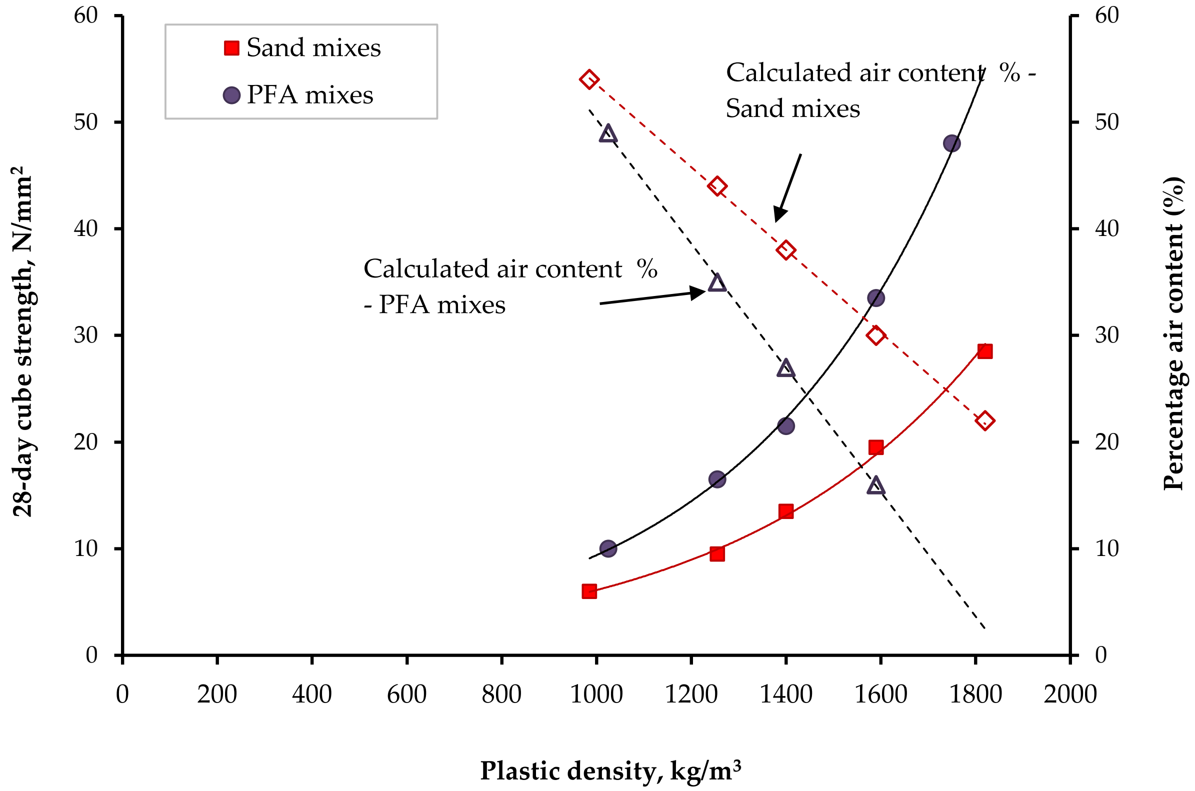


Figure 2.7: Effect of air content on compressive strength (Dhir et al. 1999)

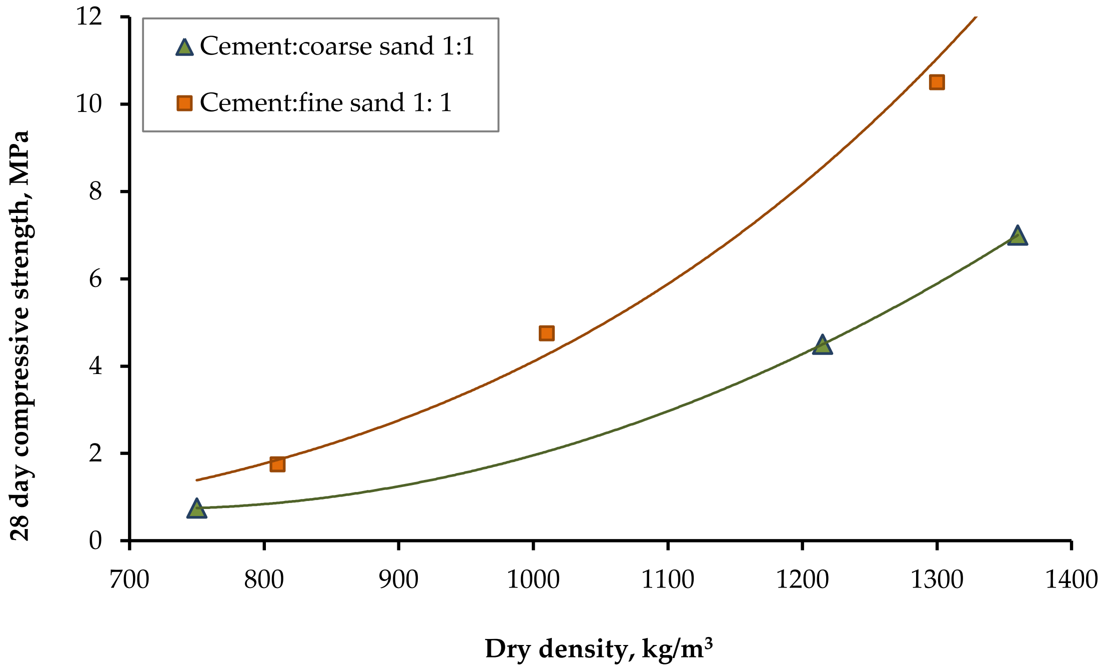


Figure 2.8: Strength density variation for mixes with sand of different fineness (Nambiar and Ramamurthy, 2006b)

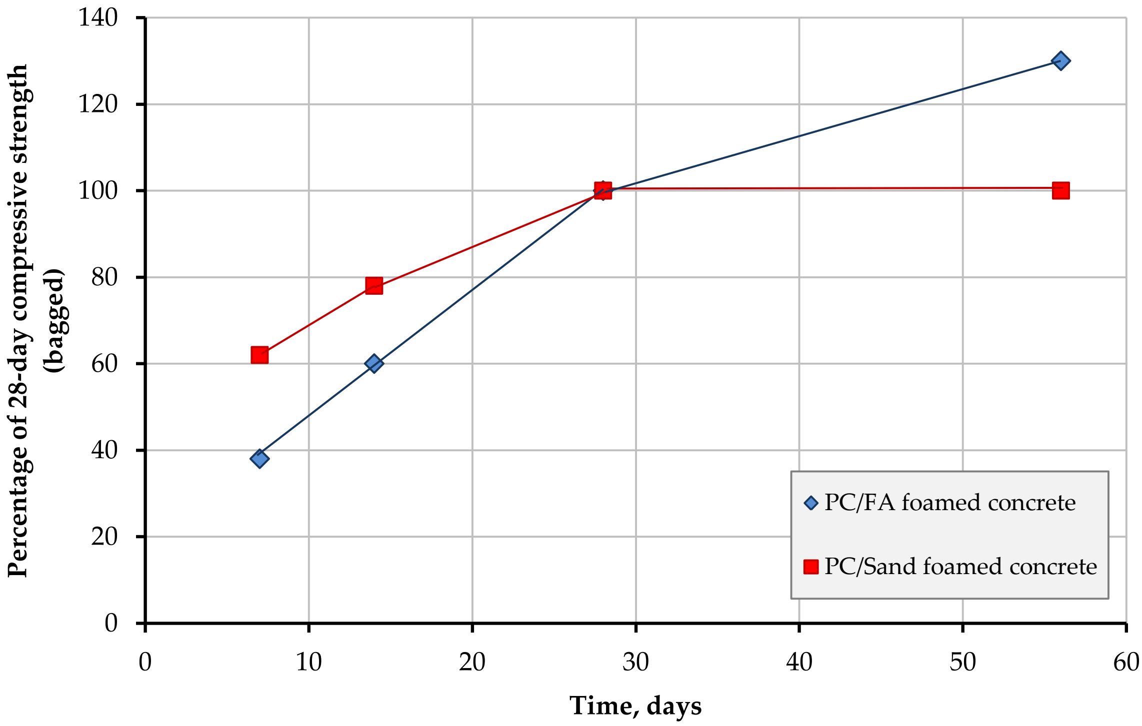


Figure 2.9: Comparison of early and longer term development of FA and sand mixes as percentage of 28-day compressive strength (Jones, 2000)

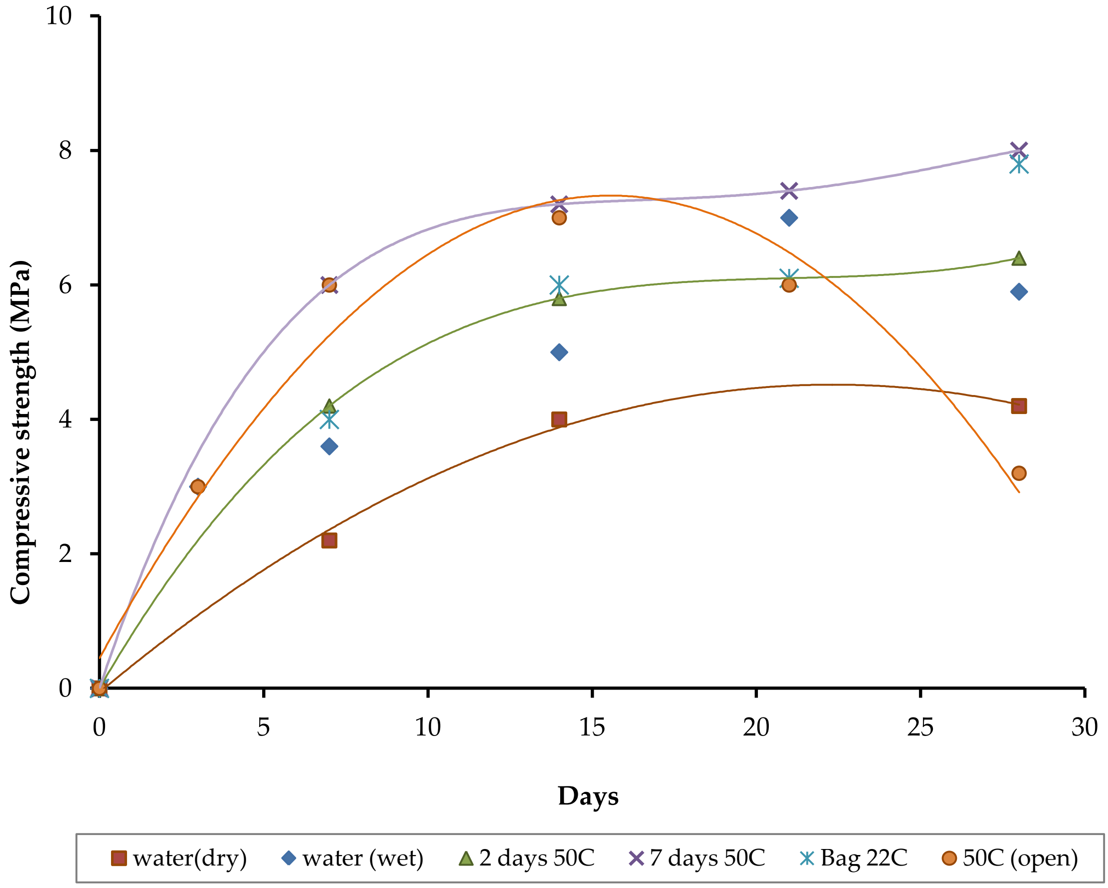


Figure 2.10: Effect of curing on compressive strength (Kearsley, 1996)

2.9.2.2 Tensile and flexural strength

The tensile strength of foamed concrete (subject to bending) is increased with increase in density of the mix. Van Dijk (1991) reported (56-day) tensile strengths of 0.06, 0.17, 0.32 and 0.51 for mixes having plastic densities of 600, 900, 1200 and 1500 kg/m^3 respectively. The tensile splitting strength of 'structural grade' foamed concrete was found to be slightly lower than the estimated lightweight concrete, as shown in Table 2.4 (Jones, 2000). PC/sand mixes had higher splitting tensile strengths compared to the PC/FA mixes. The relationship of the two is significantly different, as shown in Figure 2.11. This difference is possibly due to the strength contributed by interlocking aggregates.

The flexural strength of low density foamed concrete is reduced with increasing w/c ratio (De Rose and Morris, 1999). The addition of 12mm long polypropylene fibres was found to have increased the tensile strengths of foamed concrete (Kearsley and Visagie, 1999). Similarly, the addition of a low percentage of 19mm polypropylene fibres had also shown a substantial increase in flexural strengths, as shown in Table 2.5 (Mellin, 1999). However, the inclusion of fibres caused a loss in workability of foamed concrete (Jones and McCarthy, 2005b) as well as increase in cost (Highways Agency and TRL, 2001).

2.9.2.3 Freeze thaw resistance

Foamed concrete does not suffer significantly when exposed to a freeze-thaw cycle (BCA, 1994 and Basiurski, 2000). Even after numerous severe freeze/thaw cycles of -18 to 20^{0}C, foamed concrete with dry densities between 800 and 1400 kg/m^3 has been proven to exhibit very good freeze/thaw resistance, (Basiurski, 2000). In a study of dry density 1400 kg/m^3, both PC/FA and PC/sand mixes showed good freeze/thaw resistance (Jones, 2000). This is due to the cellular structure in the foamed concrete where the hollow voids provide the additional space and the volume required for the expansive forces during freezing in the concrete. However, in the same study, it was found that the performance of a denser mix (1800 kg/m^3) was much poorer which was attributed to the lower void content.

Table 2.4: Splitting tensile strength of sand and FA foamed concrete in compared with normal weight and lightweight aggregate concrete (Jones, 2000).

Fine aggregate Type	Plastic density kg/m^3	28-day compressive strength N/mm^2	Splitting Tensile Strength (N/mm^2)		
			Foamed concrete	Normal weight	Lightweight aggregate
Sand	1400 1600 1800	13.5 19.5 28.5	0.8 1.8 2.1	1.2 1.6 2.1	1.3 1.7 2.2
PFA$_c$	1400 1600 1800	21.5 33.5 48.0	1.5 2.0 2.5	1.7 2.3 3.0	1.8 2.4 3.1

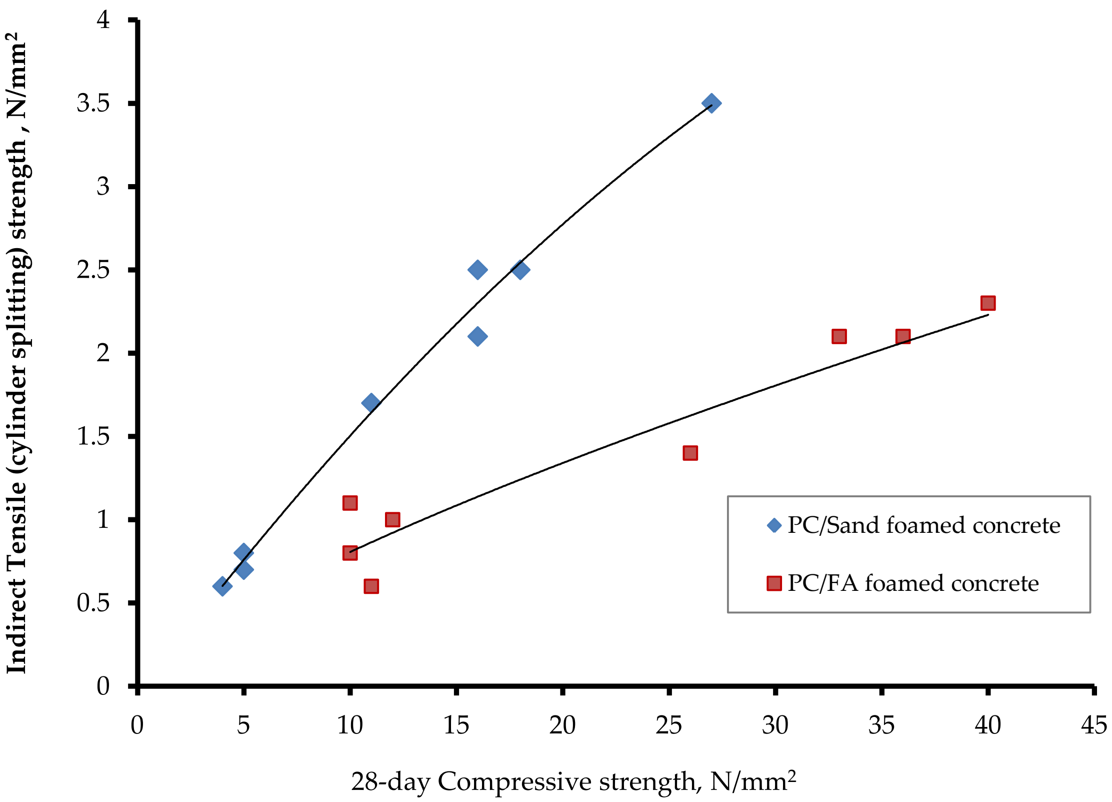


Figure 2.11: Relationship between cylinder splitting strength and 28 day cube compressive strength (Jones 2000)

Table 2.5: Effect of polypropylene fibres on compressive strength, splitting strength and modulus of elasticity of foamed concrete beams (Mellin, 1999)

Plastic density kg/m³	Fibre content [1] %	Compressive strength[2] N/mm² 2 day	7 day	28 day	Flexural strength N/mm²	Modulus of elasticity kN/mm²
1400	0.00	9.0	15.0	25.0	1.3	10.0
	0.25	17.0	35.0	62.0	4.1	19.0
	0.50	14.0	22.0	22.0	2.9	17.0
1600	0.00	8.0	16.0	26.0	1.0	4.0
	0.25	13.0	30.0	43.0	2.5	18.0
	0.50	16.0	33.0	58.0	3.2	18.5

[1] 19 mm length polypropylene fibres

[2] Sealed cured

2.9.2.4 Static Modulus of elasticity (E-value)

The stress strain relationship in any material is of vital interest in any structural design to establish the behaviour, deformation types, elasticity and the elastic limit, which represents the maximum allowable stress before the material undergoes permanent deformation. Modulus of elasticity is the ratio between stress and strain, which, in concrete, depends on the stiffness of the constituents and their relative proportions in the mix. The modulus of elasticity of concrete varies from 14 kN/mm^2 to 40 kN/mm^2 (Neville, 1995; Mehta et al., 2006).

The modulus of elasticity in foamed concrete is significantly lower than in normal concrete. The values for density range between 400 kg/m^3 to 1600 kg/m^3 were found to be within 0.8 kN/mm^2 to 12 kN/mm^2 (BCA, 1994) as shown in Table 2.3. Similar E-values were found to be between 1.0 kN/mm^2 to 8.0 kN/mm^2 for foamed concrete of dry densities between 500 kg/m^3 and 1500 kg/m^3 (Dransfield, 2000). For the same strength, the sand mixes showed higher values compared to fly ash mixes as shown in Figure 2.12 (McCarthy, 2004). This is understandable as the modulus of sand is higher than fly ash, thus there are higher E-values of sand mix foamed concrete. The addition of 0.50% polypropylene fibres by volume showed significant increases in the moduli of elasticity of foamed concrete (Mellin, 1999) as shown in Table 2.5. However, the values are still lower than in normal concrete which explains for the high deflection and brittle failure observed in the study of full-scale foamed concrete beam (Jones and McCarthy, 2005a).

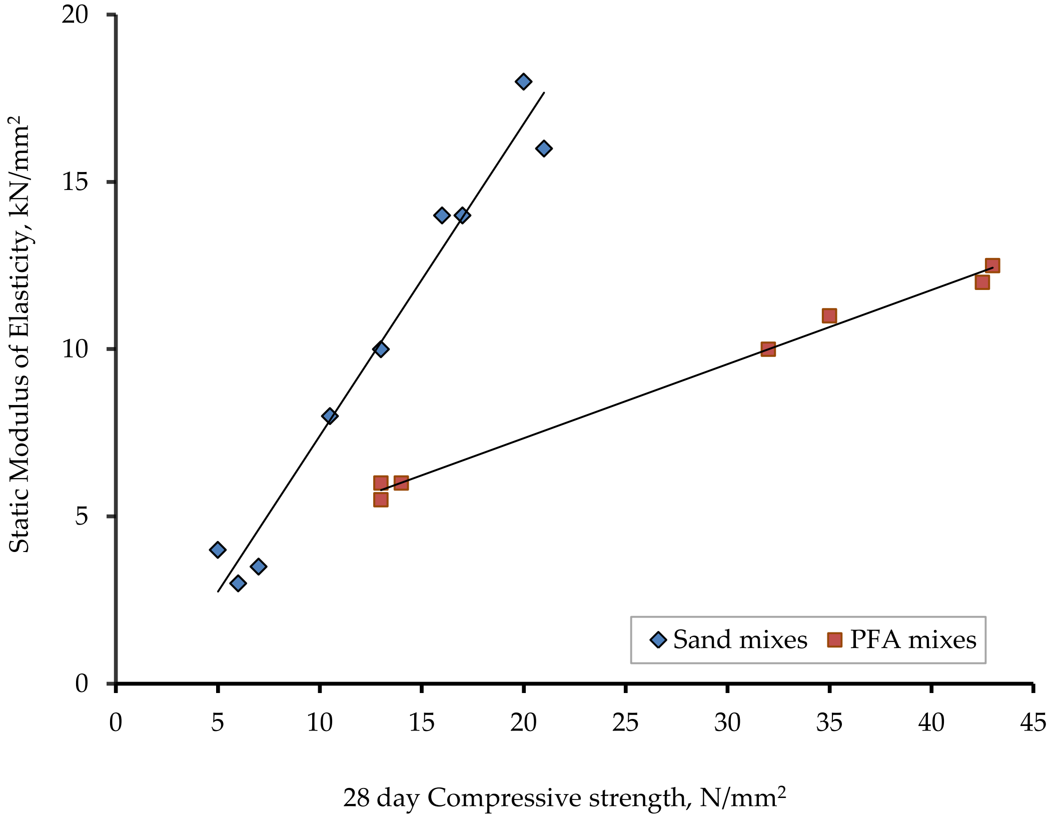


Figure 2.12: Comparison of the relationship of E value and 28-day cube strength of all mixes (McCarthy, 2004)

2.9.2.5 Bubbles Microstructure

Pore structure is a very important microstructural characteristic in a porous solid. The distribution of the pores of various sizes influences their physical and mechanical behaviours and controls the durability of the material (Kalliopi, 2006). Changes in the microstructure of a material can change its properties significantly (Kumar, 2005). These pores are mainly classified according to their size and types as illustrated in Table 2.6 (Kalliopi, 2006). Voids are identified as having the biggest size in the range, between 50μm to 200μm. The shapes of the voids are spherical and not interconnected (Mehta et al. 2006; Kalliopi, 2006). However, voids in normal concrete are either entrapped inadvertently during mixing and placing of concrete or intentionally entrained using air-entraining chemicals (Neville, 1995; Kalliopi, 2006).

In foamed concrete, the addition of preformed foam produces air voids which are uniformly distributed in matrices of fillers and cements (Tiong et al., 2006). Most researchers are in accord on the paramount importance of adequate void system for the production of foamed concrete (Kearsley 1999; Narayanan and Ramamurthy, 2000a; Aldridge, 2005; Hamidah et al., 2005; Nambiar and Ramamurthy, 2007a). The parameters of the air voids which include shape, spacing factor and size distribution confer the important properties of foamed concrete (Nambiar and Ramamurthy, 2007a). The skin of the air voids must be tough and persistent since the air voids are separated and coated with cement paste during mixing and placing (Wee et al., 2006). All these properties are responsible for the tenfold change in compressive strength, rather than common w/c ratio and aggregate-cement ratio as in conventional concretes (Beningfield et al., 2005). The range of sizes of air voids in foamed concrete varies from 0.1 mm to 2 mm (Aldridge, 2005; Highways agency and TRL, 2001; Cox, 2005; Nambiar and Ramamurthy 2007a). Parameters affecting the difference in sizes and distribution of the air voids are densities, w/c ratio, constituent materials and additives (Nambiar and Ramamurthy, 2007a; Wee et al., 2006).

Nambiar and Ramamurthy (2007a) reported several findings, which included the facts that:

1. the number of larger voids increased with increased in foam volume;

2. at low dosage of foam volume, the air-void distribution is more uniform than at high foam volume content;

3. when the density was increased, the voids were more distinct and spherical in shape, as illustrated in Figure 2.13. The median void diameters and values of D50 and D90 (10% oversized voids) became smaller and more uniform in size (Figure 2.14).

4. a reduction in strength corresponded to an increase in diameter, even though this change is not significant at higher densities (Figure 2.15);

5. the values of D90 showed better correlation with strength compared to D50; this suggested that bigger pores influenced the strength more compared to smaller pores; and

6. cement-fly ash mixes produced voids of a more uniform distribution and smaller diameter size in all densities. This characteristic suggested that fineness of the filler had a considerable effect on the voids by providing a more uniform coating of the paste on the bubbles, thus preventing them to merge and overlap. Similar observations were made through a study on fineness of sand on compressive strength of foam concrete (Nambiar and Ramamurthy, 2006b).

Table 2.6: Classification of pore sizes according to the general classification by the IUPAC and to the concrete science terminology (Kalliopi, 2006)

<table>
<tr><td colspan="2">According to IUPAC</td><td colspan="2">According to P. Mehta, 1986 (1.40)</td><td colspan="6">According to S. Mindness et al. 2002 (1.4)</td></tr>
<tr><td>Name</td><td>Diameter</td><td>Pore type</td><td>Size range</td><td colspan="3">Name</td><td>Diameter</td><td>Role of water</td><td>Paste properties</td></tr>
<tr><td rowspan="2">Micropores</td><td rowspan="2">Up to 2nm</td><td rowspan="3">Interparticle space between C-S-H sheets</td><td rowspan="3">1 nm to 3 nm</td><td>Micropores “inter layer”</td><td rowspan="3">Gel pores</td><td rowspan="2"></td><td>Up to 0.5 nm</td><td>Structural water involved in bonding</td><td>Shrinkage, creep at all RH</td></tr>
<tr><td>Micropores</td><td>0.5 nm to 2.5 nm</td><td>Strongly adsorbed water; no menisci form</td><td>Shrinkage, creep at all RH</td></tr>
<tr><td rowspan="2">Mesopores</td><td rowspan="2">2nm to 50 nm</td><td>Small (gel) capillaries</td><td rowspan="2">Capillary pores</td><td>2.5 nm to 10 nm</td><td>Strong surface tension forces generated</td><td>Shrinkage between 50% and 80% RH</td></tr>
<tr><td>Capillary pores (low w/c)</td><td>10 nm to 50 nm</td><td>Medium capillaries</td><td rowspan="3">Hollow –shell pores</td><td>10 nm to 50 nm</td><td>Moderate surface tension forces generated</td><td>Strength, permeability, shrinkage at high RH> 80%</td></tr>
<tr><td rowspan="2">Macropores</td><td rowspan="2">> 50 nm</td><td>Capillary pores (high w/c)</td><td>3 µm to 5 µm</td><td>Large capillaries</td><td rowspan="2"></td><td>50 nm to 10 µm</td><td>Behaves as bulk water</td><td>Strength, permeability</td></tr>
<tr><td>Entrained voids</td><td>50 µm to 1 mm</td><td>Entrained air</td><td>0.1 mm to 1 mm</td><td></td><td>Strength</td></tr>
</table>

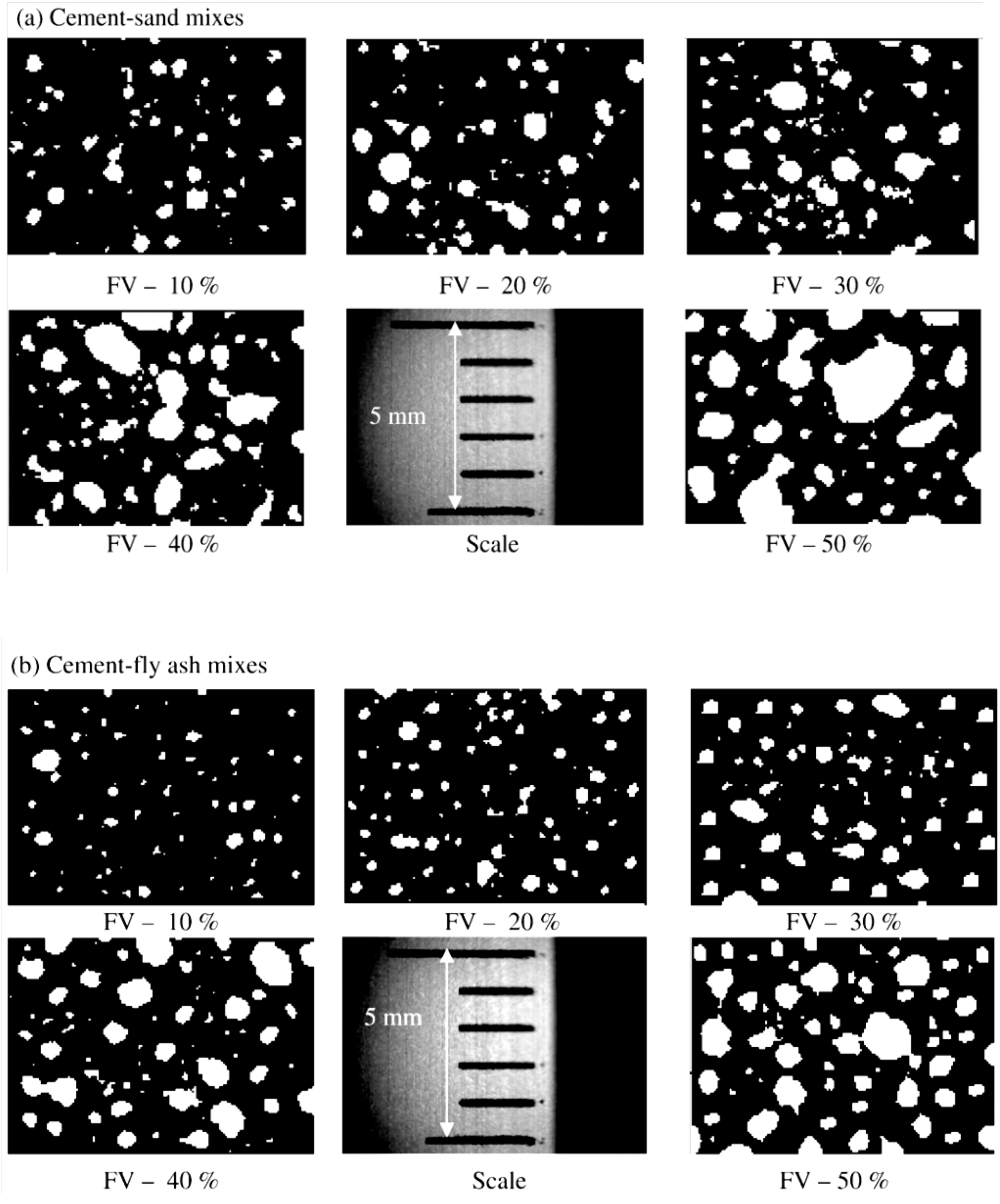


Figure 2.13: Typical binary images (Nambiar and Ramamurthy, 2007)

a. Cement-sand mixes

b. Cement-fly ash mixes

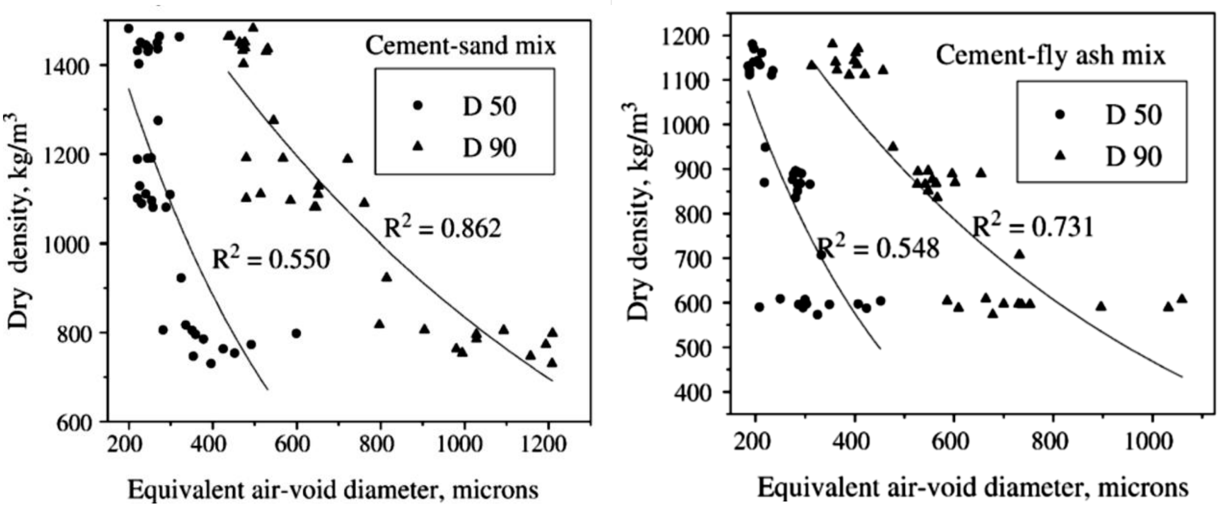


Figure 2.14: Density vs. air-void distribution (Nambiar and Ramamurthy, 2007)

a. Cement-sand mix

b. Cement-fly ash mix

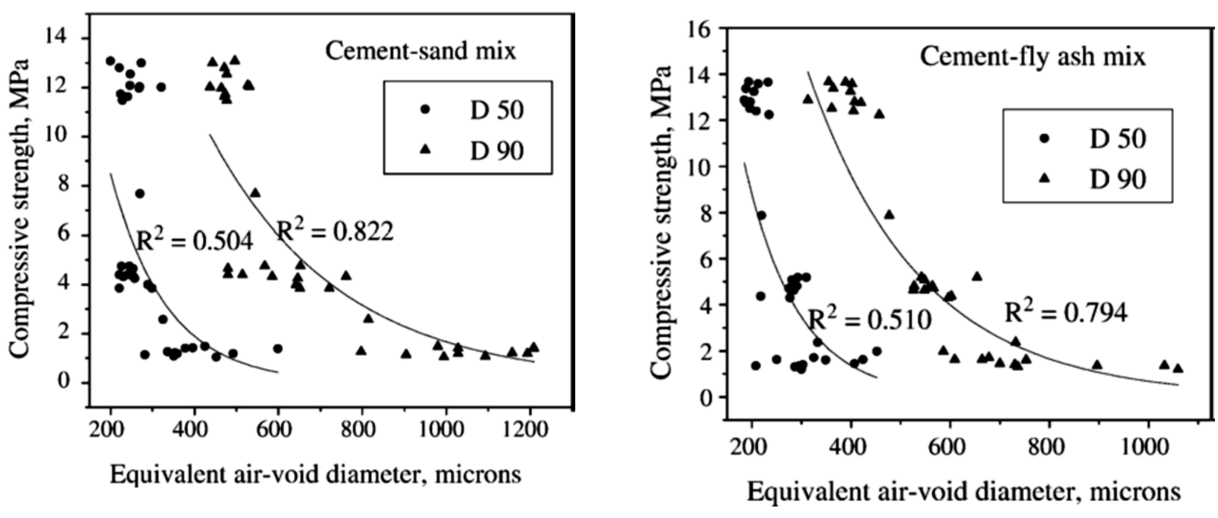


Figure 2.15: Strength vs. air-void diameter (Nambiar and Ramamurthy, 2007)

a. Cement-sand mix

b. Cement-fly ash mix

2.10 SUMMARY OF THE LITERATURE

In the literature review, the potential of foamed concrete has been acknowledged as construction material with vast advantages whilst accepting its limitations. Regardless of limited specifications and tests that are available for the use of foamed concrete, the amount of usage is increasing every year.

It is well agreed in the literature review that constituent materials and mix proportions affect the properties and behaviour of foamed concrete. The possible effect of different constituent materials on the properties had been recognized from literatures and through past researches. Previous researchers at the Concrete Technology Unit in the University of Dundee investigated on the strength and thermal properties. Other researches included the use of recycled aggregates and minimal aggregates for sustainability. Published data by other researchers had shown that different aspects of properties of foamed concrete had also been studied. However, rheology is one of the important aspects, which has not been well investigated in foamed concrete. The importance of the rheological properties of all cementitious materials has been acknowledged and has been accepted as having direct relation to the behaviour. Further research has to be been done to investigate the effect of constituent materials and the mix proportion on the rheological properties of foamed concrete. This knowledge will be useful to predict the overall behaviour and for practical applications. Another important area that requires more research is the understanding of bubble structures which is known to vary with different mix proportions and constituent materials.

The importance of foam stability had been mentioned in the literature. Instability in foam caused collapse in foamed concrete which lead to segregation and variation in density. Hence, the factors leading to instability will be investigated.

An attempt will be made to formulate all findings to conclude the effect of constituent materials and mix proportion on these major areas of research on foamed concrete.

CHAPTER 3: EXPERIMENTAL PROGRAMME: MATERIALS AND TEST METHODS

3.1 INTRODUCTION

Foamed concrete has been identified as a versatile construction material with excellent properties that include being light, durable, simple to use, environmentally sustainable and versatile without being restricted by factory requirements (Jones and McCarthy, 2005). The use of foamed concrete is recognised as suitable for lower strength applications (BRE, 2004; Highways Agency and TRL, 2001). However, the potential of foamed concrete to be used as structural element has been inhibited by perceived difficulty in achieving high strength and unfamiliarity of its characteristics (Jones and McCarthy, 2005).

This study fell into two chronological phases which cover year 2005 and 2007-2009. The experiments conducted in 2005 were preliminary and were intended to investigate the possibility of foamed concrete being used as a structural element. The second phase of experiments complemented the pilot study.

In phase one (2005), following the study of carbon steel used in reinforced foamed concrete investigated by Jones and McCarthy (2005b), a full-scale pilot study of post-tensioned foamed concrete beam was conducted using glass-fibre reinforced plastic. The outcome from this work demonstrated that the beam experiment was unsatisfactory.

Therefore, in phase 2 of the current study, (2007-2009), further examination of foamed concrete was conducted. These two phases encompassed four studies. Study 1 was on post-tensioned foamed concrete beam which, as noted, gave unsatisfactory outcomes. Studies 2, 3 and 4 followed a different approach. For each study, a different methodology was adopted. Each will be discussed in subsequent chapters.

3.2 EXPERIMENTAL PROGRAMME

As shown in Table 3.1, the experimental programme started with performing a literature review followed by experimental works. These experiments were divided into two chronological phases, the first phase was done in 2005 and the second phase was completed in 2007-2009 as noted above.

Preliminary studies were done in phase one and were intended to investigate the possibility of foamed concrete being used as structural element. In this phase, the behaviour of full-scale post-tensioned foamed concrete beam was studied. The density of the foamed concrete beam was 1400 kg/m^3 following a previous study by Mellin in 1999. However, the tensioned-end slipped during the test and could not validate the viability of foamed concrete being used as a structural element.

Following unsatisfactory results from phase one, a different approach was adopted in phase two where the characteristics and behaviour of foamed concrete were studied. The three main characteristics of foamed concrete examined were the rheological properties, microstructure, and instability. Subsequently, the relationship between each characteristic was also studied.

The importance of the rheological behaviour of other cement-based materials can be attested in the literature (Banfill, 2003; Roussel, 2007; Hanehara and Yamada, 2008). However, the study of rheology in foamed concrete is very limited. Foamed concrete was noted as having self-flowing and self-compacting rheology (Jones et al., 2003) who further noted that the mix using coarse fly ash, FA_c exhibited enhanced consistency and rheology in foamed concrete (Jones and McCarthy, 2005a). In this current study, the rheological properties were studied in depth. The empirical values of yield stress and plastic viscosity of different mixes of foamed concrete were obtained using a Brookfield Viscometer. For the study of rheological properties, the Marsh cone test was employed in addition to the Brookfield viscometer, as described in Chapter 5.

As foamed concrete has typical air content of 40 to 80 per cent of the total volume and bubbles varying from 0.1 mm to 1.5 mm in diameter (Highways Agency and TRL, 2001), the microstructure of foamed concrete is intriguing. The aim of this part of study was to examine the bubble characteristics in relation to materials constituents, densities, water/cement (w/c) ratio and the effect of additions to the mixes. In this experiment, the digital images of a selected range of foamed concrete were analysed. For the study of the microstructure, the hardened specimens were split open and investigated. The details of the method and the findings are discussed in Chapter 6.

The study of instability in foamed concrete was the third part of these investigations. In the study of instability, the drop after 24 hours in the surface level of the specimen was recorded for each mix. The details of these tests and results are presented in Chapter 7. This phase of study formed the concluding part which combined the results of the previous two studies: microstructural characteristics and the study of rheological properties.

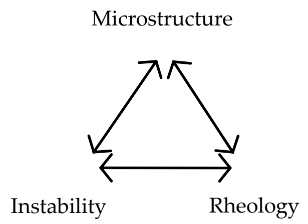
Throughout the study in phase 2, the main selected densities were 600, 1000 and 1400 kg/m^3 which are expected to show a good range. Other densities were also experimented for comparison purposes. These densities also relate to the literature obtained and reflect comparable previous researches done in the University of Dundee (Yerramala, 2008; Rao, 2008). A cement content of 300 kg/m^3 was maintained throughout phase 2 experiments following research conducted by Jones (2000) which reported that an increase in content above 500 kg/m^3 did not show significant gain in strength. The w/c ratio was mainly kept at 0.40 to 0.80 in most specimens, although other ratios were included briefly.

Table 3.1: Experimental Programme

DEVELOPMENT OF FOAMED CONCRETE : ENABLING AND SUPPORTING DESIGN

<table>
<tr><th colspan="5">LITERATURE REVIEW</th></tr>
<tr><td rowspan="2">PHASE 1
2005</td><th colspan="2">TEST PROGRAMMES</th><th colspan="2">EXPECTED FINDINGS</th></tr>
<tr><td>PERFORMANCE OF MODEL STRUCTURAL ELEMENT

Viability of using foamed concrete as structural member</td><td>Full scale post-tensioned beams
Materials
• Cement – CEM I 42.5N
• Coarse fly ash, FA_c 100%
• Synthetic surfactant
• Superplasticiser</td><td colspan="2">Effect of post-tensioning on foamed concrete beam
To confirm the status of foamed concrete as a structural material</td></tr>
<tr><td rowspan="3">PHASE 2
2007 - 2009</td><td>RHEOLOGY

Study of rheological properties</td><td>i. Brookfield Viscometer
ii. Marsh cone test
Materials
• CEM I 42.5N, Metakaolin, FA_f
• Sand, FA_c
• Protein surfactant</td><td>Empirical values
• Yield stress
• Plastic viscosity
• Flowability</td><td rowspan="3">
</td></tr>
<tr><td>MICROSTRUCTURE

Microstructural characteristics</td><td>Image analysis
Materials
• CEM I 42.5N, CSA
• Surfactants -Protein ,synthetic
• Wetting agent</td><td>Microstructural analysis

• Bubble diameter
• Bubbles count
• Characteristics</td></tr>
<tr><td>CAUSES OF INSTABILITY

Study of parameters affecting instability</td><td>i. Dropout test
ii. Drop in level
Materials
• CEM I (42.5N, 52.5R), CSA, Metakaolin, FA_f
• Sand, FA_c
• Protein and synthetic surfactants</td><td>Factors leading to instability</td></tr>
</table>

3.3 Constituent Materials

3.3.1 Cements

1. Portland Cement

Portland cement (CEM I 42.5N conforming to BS EN 197: Part 1: 2000) is usually used as the main binder for foamed concrete.

In most experiments in these studies, the total cementitious material was kept at 300 kg/m^3. Typically, cementitious content lies between 300kg/m^3 and 400 kg/m^3 although up to 500 kg/m^3 has been used to attain higher strength concrete. The gain in strength obtained by increasing the content above 500 kg/m^3 is small (Jones, 2000), as mentioned previously. However, in the study of structural performance of foamed concrete (discussed in Chapter 4), the cement content used was 600 kg/m^3. This was selected because the aim of the experiment was to study the potential of foamed concrete as a structural material; hence, the highest strength possible was very important.

Other combinations of cements were also used in the studies of microstructure, rheological properties and instability in foamed concrete.

The properties of these cements are given in Table 3.2. All cements are stored properly in plastic bags to prevent moisture penetration and subsequent deterioration.

Table 3.2: Characterisation of the cementitious materials

PROPERTIES	CEMENTITIOUS MATERIALS		
	PC	Pt 1 Fly Ash	MK
Physical Properties			
Density (g/cm^3)	2.99	2.14	2.60
Fineness - 45 μm retention (%)	-	5.90	0.00
Fineness - Blaine (cm^2/g)	3550	4285	29960
Fineness - PSD (cm^2/g)	4450	5625	15755
Setting time (hh:mm)	2:05	2:25	-
LOI (%)	-	2.08	1.34
Particle Size distribution			
D90 (μm)	34.24	47.33	8.07
D50 (μm)	12.38	14.07	1.90
D10 (μm)	1.64	1.85	0.69
Water Requirement and Activity			
Water Requirement	100	91	-
Strength Factor	1.00	0.81	-
Activity Index	100	83	-
Chemical Compositions (%)			
CaO	62.70	7.19	0.01
SiO_2	21.32	51.22	56.77
Al_2O_3	5.86	27.30	39.87
Fe_2O_3	3.62	3.60	0.51
MgO	2.39	1.35	0.29
MnO	0.10	0.04	0.01
TiO_2	0.32	1.38	0.00
K_2O	0.70	1.55	1.82
Na_2O	0.21	0.58	0.096
SO_3	2.99	0.46	0.00
Mineralogical Components			
C_3S	41.2	-	-
C_2S	19.9	-	-
C_3A	7.8	-	-
C_4AF	15.4	-	-
Quartz	1.0	8.6	1.8
Mullite	0.9	23.4	-
SiC	-	-	-
Illite	-	-	3.3
Sandine	-	-	9.8
Amorphous material	7.3	63.0	85.1

2. Fly Ash

'Fine' fly ash (FA_f) with a 45 μm sieve retention of 7.5%, loss on ignition (LOI) of 5.0% and conforming to BS EN 450.5 was used to replace CEM I 42.5N at 30% by mass fraction.

The literature shows that the use of FA_f cement has been proven to effect a significant change in strength and other fresh and hardened properties of foamed concrete (Jones and McCarthy, 2005b; Jones and McCarthy, 2006; Nambiar and Ramamurthy, 2008). For that reason, this cement type is included in these characteristic investigations.

3. Metakaolin

Metakaolin (MK) is a pozzolanic material which is highly active and effective pozzolan for the partial replacement of cement in concrete. It is an ultra-fine material, obtained by the calcination of kaolinitic clay at a temperature ranging between 500°C and 800°C. The raw material input in the manufacture of metakaolin ($Al_2Si_2O_7$) is kaolin. Metakaolin on reaction with $Ca(OH)_2$, produces CSH gel at ambient temperature and reacts with CH to produce alumina containing phases (Siddique and Klaus, 2009). The specific surface area of metakaolin is very high, in the range of 4000m^2/kg to 12000m^2/kg (Neville, 1996), hence the water requirement is high. Even though metakaolin has the potential to improve the performance and enhance the durability of concrete, its use in tests and applications are limited because of its high cost (Bai and Wild, 2002). The inclusion of metakaolin in concrete improved several mechanical properties of concrete such as increased compressive and flexural strengths, reduced permeability, increased resistance to chemical attack, increased durability, reduced effects of alkali-silica reactivity (ASR), reduced shrinkage, enhanced workability and finishing of concrete (Siddique and Klaus, 2009). The incorporation of metakaolin, up to 25% in blended cements, has shown pore refinement to 63% of the original pore size (Frı´as, 2006).

No literature has been published on the use of metakaolin in foamed concrete. However, it has been noted that the use of metakaolin was possible to increase the strength of foamed concrete (Jones, 2000). In the study of rheology, microstructure and instability in foamed concrete, metakaolin was used as replacement of cement to a level of 20%.

4. Calcium sulphoaluminate (CSA)

Calcium sulphoaluminate (CSA) cements have been produced, used and standardized in China for about 30 years and not widely used in Europe and the U.S. They are known as the "third cement series" (Juenger et al., 2010). It was designed by the China Building Materials Academy (CBMA) and was intended to manufacture self-stress concrete pipes because it has swelling properties (Pe´ra and Ambroise, 2003). CSA cements contain ye'elimite (C_4A_3S) as a major constituent (30-70%). CSA cements are rapid-hardening, high strength, expansive, or self-stressing cements. They have been used in China as a binder for concrete in bridges, leakage and seepage prevention projects, concrete pipes, precast concrete (e.g. beams and columns), prestressed concrete elements, waterproof layers, glass fiber reinforced cement products, low temperature construction and shotcrete. Due to their low pH, low porosity and the ability of ettringite and AFm phases to bind heavy metals, CSA cements and their blends with Portland cement are of interest in the field of hazardous waste encapsulation (Juenger et al., 2010).

CSA cements provide a low CO_2 alternative to Portland cement. It releases less than half CO_2 per g of cementing phase compared to Portland Cement. The firing temperature used to produce CSA clinker is about 200 °C lower than that used for Portland cement clinker.

The setting times of CSA cements depends on their ye'elimite content, the kind and content of minor phases, and the amount and reactivity of the added calcium sulfate. Typical values are between 30 min and 4 hours. Compared to Portland cement, CSA cements reach higher early and late strengths. The durability of building materials made from CSA cements was found to be comparable to conventional Portland cement-based materials, although more studies are required for the long-term behaviour. Carbonation was found to be more rapid in CSA cements compared to Portland cement concretes, leading to the decomposition of ettringite which led to moderate strength loss. The alkalinity of CSA cements is about 1 pH unit lower than for Portland cement, which decreases protection from corrosion of steel reinforcement and alkali aggregate reaction (Juenger et al., 2010). The CSA used in this research project was labelled QuickCem which was provided by Castle cement. The chemical compositions of the cements and fillers are shown in Table 3.3.

Table 3.3: Chemical composition of cements and fillers, % by mass

Compound	CEMENTS			AGGREGATE/FILLER	
	CEM I (42.5N)	CSA	FA_f	SAND	FA_c
CaO	62.70	42.25	7.19	1.50	3.40
SiO_2	21.32	10.96	51.22	78.50	50.90
Al_2O_3	5.86	29.93	27.30	10.50	28.00
Fe_2O_3	3.62	3.01	3.60	3.00	4.20
MgO	2.39	1.45	1.35	0.90	1.20
MnO	0.10	-	0.04	-	0.05
TiO_2	0.32	-	1.38	0.50	1.40
K_2O	0.70	1.02	1.55	1.60	1.50
Na_2O	0.20	0.23	0.58	2.00	0.50
P_2O_5	0.05	-	1.4	-	0.70
Cl	0.07	0.01	0.05	<0.01	0.02
SO_3	2.99	8.82	1.30	0.10	2.70

3.3.2 Fillers

1. Fine aggregates /sand

The main type of fine aggregate to be used throughout this study is sand of medium grade conforming to BS EN 12620: 2002. The sand was air-dried in the laboratory to a surface dry condition and sieved through a 2.36 mm sieve. Only finer aggregates were used, because coarser aggregate may settle in the lightweight mix and cause collapse of the foam during mixing (Sach and Seifert, 1999 cited in Jones, 2000). However, in the study of rheology, a finer size, sieved through a 1 mm sieve was used to accommodate the apparatus used.

2. Coarse Fly Ash (FA_c)

Coarse fly ash, FA_c with a 45 μm sieve retention conforming to BS 3892: Part 2: 1997 or BS EN 450: 1995 was used.

The advantageous influences of FA_c on the consistency of foamed concrete have been reported (Jones et al., 2003; Jones and McCarthy, 2005a). For the same w/c ratio, the actual water content of the corresponding FA_c/fine aggregate concretes was higher which increased flowability. This enhanced consistence of the FA_c concretes is attributed to the 'ball-bearing effect' of FA particles due to their spherical morphology improved packing of the solid phase and adsorption of mix water on to the FA_c particles reducing inter-particle friction (Jones and McCarthy, 2005a). In addition, a more uniform distribution of air voids was developed in the foamed concrete with FA_c blend compared to foamed concrete using sand only mix (Nambiar and Kunhanandan, 2007a).

3.3.3 Surfactants

There are several types of surfactants available in the market. The main surfactants used in this study were the ones which were commercially available as these have been proven to be effective in producing foamed concrete. A synthetic-based surfactant and two types of protein-based surfactants, Protein 26 and Protein 40 were used widely throughout the study (Figure 3.2). Foamed concrete produced with a protein surfactant was found to have a strength/density ratio of about 50% to 100% higher compared to those employing synthetic surfactants (McGovern, 2000). Besides the surfactants mentioned, two other commercially available synthetic-based surfactants (TFAL-3 and Regular-3%) were briefly included for comparison in the study of instability.

The concentration of the surfactant solution used for the production of foam is typically 60 g per litre of water, which is used throughout most of the study to produce foam of 50 ± 5 kg/m^3 density. The preformed foam was prepared from a 6% aqueous surfactant solution in a dry system generator. The typical density was found to be between 40 and 50 kg/m^3.

3.3.4 Water

Water used in this study was usually normal tap water of pH within the range 6.8 to 7.0, which was conformed to BS EN 1008 Mixing water for concrete. However, in the study of instability, distilled water and water of different pH values and temperatures were included.

The 'free' water is the amount after allowance has been made for actual or potential absorption by the aggregate of which only a part is required for reaction with the cement, while the rest is present simply to make the mix sufficiently workable for the intended use (Tattersall, 1991).

Water/cement ratio (w/c ratio) is a significant factor in foamed concrete; too little water potentially leads to disintegration, too much water leads to segregation (Kearsley, 1999, Highways Agency and TRL, 2001 and Nambiar and Ramamurthy, 2006b). In addition, w/c ratio of the base mix required to achieve adequate workability is dependent upon the type of binder(s), the required strength of the concrete and whether or not a water-reducing or plasticizing agent has been used (Jones, 2001).

3.3.5 Other materials

1. Wetting agent

A commercially available wetting agent, where appropriate, was used in some studies.

2. Superplasticisers

Superplasticiser conforming to BS EN 934-2.8 was used. This superplasticiser was used because at 0.35 w/c ratio, the mix was less workable to fill up the formwork.

Superplasticisers have been used to further enhance the consistence of foamed concrete in low w/c ratios, although they are not universally added due to its high intrinsic workability and modest strength requirements (Highways Agency and TRL, 2001). The addition of superplasticisers had no adverse effects except for segregation which is noticeable when mixed with protein-based surfactants (Highways Agency and TRL, 2001). Dransfield (2000) has questioned the use of such additives, and Bartos (1992) claimed that they might reduce the stability of the foam. The dosage of superplasticisers to foamed concrete was suggested not to exceed 0.2 per cent by weight of cement and tests should be carried out to confirm compatibility of the foam and superplasticiser (Highways Agency and TRL, 2001).

Figure 3.1: Protein and synthetic surfactants

Figure 3.2: Foam

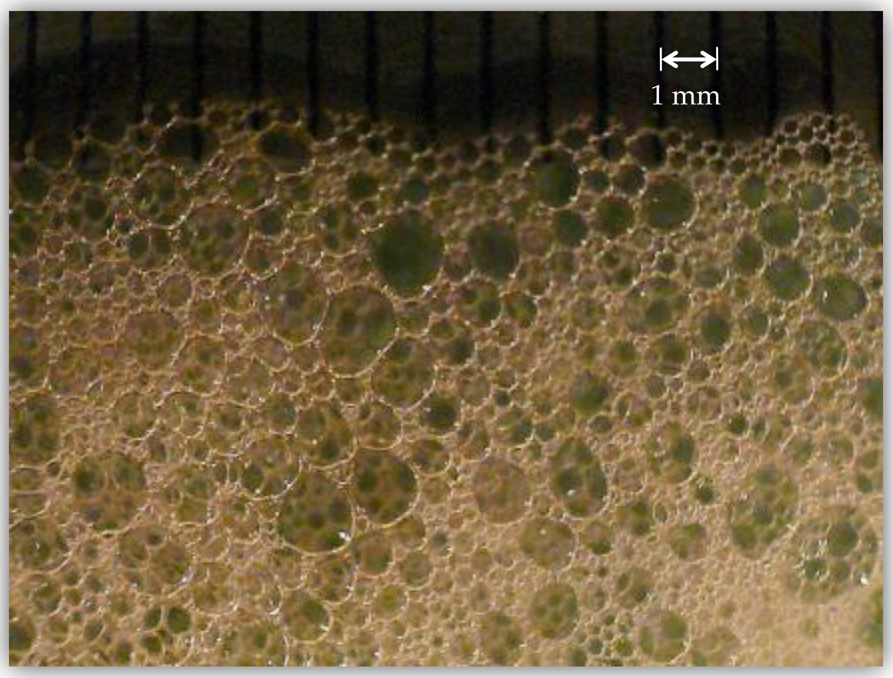


Figure 3.3: Magnified foam bubbles

3.4 MIX DESIGN

As there is no standard specification for the method of proportioning, all studies in the University of Dundee use the method that was developed by the Concrete Technology Unit, University of Dundee, as described below. In this method, the ratio of cement and water is pre-determined. The fine aggregate (sand and /or fly ash) content is calculated by equating the sum of solids and water content to the target plastic density value.

$$D = C + W + F \qquad \textit{Equation 3.1}$$

where

D = target plastic, kg/m^3

C = cement (PC and / or other cements) content, kg/m^3

W = water content, kg/m^3

F = filler (fine aggregate and/or others) kg/m^3

Adjustments to the above equation were made to include water absorption and laboratory air dry condition. The level of water contained in foam is assumed to be minimal and, therefore, is not considered in the calculations, although it is recognised that foam collapse occurs during mixing (Dhir et al., 1999). As a result of the collapse, the w/c ratio of the mix is actually slightly higher than the batched quantity. However, the degree of collapse varies with mix constituents and is unpredictable; hence this phenomenon is ignored in mix proportioning (McCarthy, 2004).

Theoretically, the amount of foam required to achieve the target plastic density is identified by calculating the volume of air in a unit volume, as shown below:

$$V_{cem} + V_{water} + V_{filler} + V_{foam} = 1m^3 \quad \text{that is } C/\rho_C + W/\rho_w + F/\rho_F + M_{foam}/\rho_{foam} \qquad \textit{Equation 3.2}$$

where

V = quantity of each material, m^3

ρ_C = density of cement, kg/m^3

ρ_F = particle density of filler, kg/m^3

ρ_w = density of water, kg/m^3 (taken as 1000 kg/m^3)

M_{foam} = quantity of foam, kg

ρ_{foam} = density of foam, kg/m^3

The range of densities of foamed concrete is not markedly defined, ranging from 300 to 1600 kg/m^3 (BCA, 1991), 400 to 1600 kg/m^3 (BCA, 1994) from 800 to 1600 kg/m^3 (Dransfield, 2000). The majority of densities of the mixes studied were 600, 1000 and 1400 kg/m^3. These densities demonstrate a good range of foamed concretes commonly used in the industry (Jones and McCarthy, 2006) and are anticipated to show significant difference in behaviour.

The most common w/c ratio was 0.50 because it provided sufficient consistency for the majority of mixes within the range of densities and constituent materials (WRAP, 2004). However, w/c ratios 0.40 to 0.80 were chosen to study the effect and observe the behavioural pattern. An illustration of the proportions of constituent materials for each density at w/c ratio 0.50 is shown in Figure 3.4 and Figure 3.5 shows the percentages for a range of w/c ratios for density 600 kg/m^3.

The cement content of the foamed concrete for the majority of studies was kept constant at 300 kg/m^3, which is comparable to other studies (Jones and McCarthy, 2006; Jones et al., 2003; McCarthy, 2004) while in the study of performance of model structural element, the cement used was 600 kg/m^3. In the study of structural performance, the cement content was increased as it was found that the minimum cement content to achieve the required strength for structural grade foamed concretes was 500 kg/m^3 (Jones, 2000). The typical mix proportions for the foamed concrete are shown in Table 3.4.

Table 3.4: Mix proportions of foamed concrete

			MIX CONSTITUENTS PROPORTIONS kg/m³			
MIX TYPE	Target plastic density, kg/m³	w/c ratio	CEM I (42.5N)	Sand	Water	Air (%)
Sand mix	600	0.4	300	180	120	72
		0.5	300	150	150	70
		0.6	300	120	180	68
Sand mix	1000	0.4	300	580	120	56
		0.5	300	550	150	55
		0.6	300	520	180	53
Sand mix	1400	0.4	300	980	120	41
		0.5	300	950	150	39
		0.6	300	920	180	38

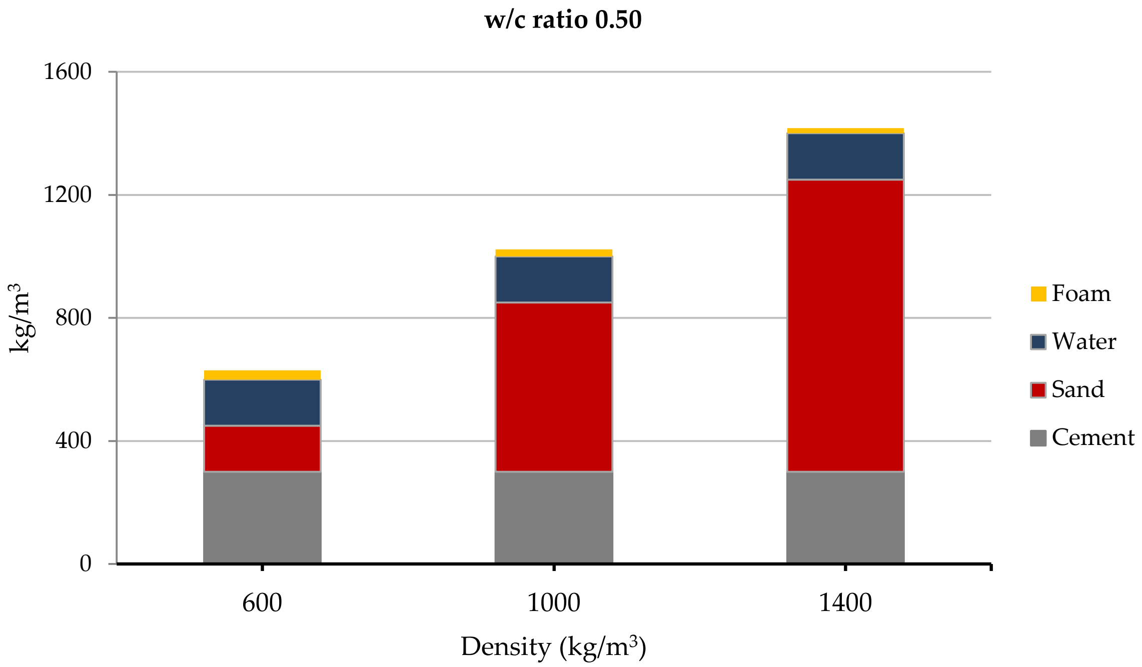


Figure 3.4: Proportions of constituent materials

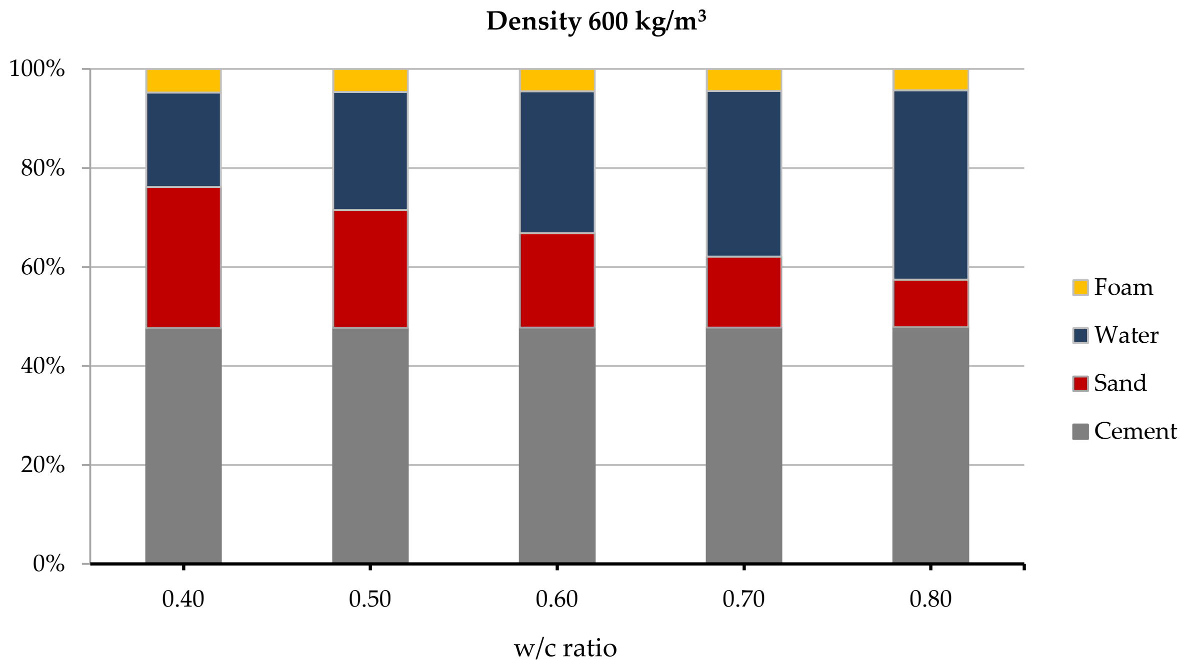


Figure 3.5: Percentages of constituent materials for different w/c ratios

3.5 FOAM GENERATOR

The foam generator used in the study is shown in Figures 3.6 and 3.7. It consists of two main chambers: the air chamber and the fluid chamber, a pump, and a diaphragm/membrane which separates them. When compressed air is directed to the pump air chamber with the main air valve, the surfactant solution is also drawn into the fluid chamber. The pressure of the diaphragm on the fluid forces it out of the pump discharge. Foam is produced to the required density by combining the solution with the compressed air and forcing it through restrictions (for example, scouring pads) in the foam lance (Figures 3.8 and 3.9).

The density of the foam is dependent on the pressure applied to the foaming solution. Throughout this current study, the pressure gauge of the foam generator was adjusted and preset to 50 psi, which reduces to 40 psi during operation. As noted by Jones (2001), above this level the decrease in foam density is not significant. The amount of air and solution entering the foam lance is adjustable to obtain foam density of 50 ± 5 kg/m^3 as this has exhibited the greatest stability (Jones et al., 2003).

The density is established before adding to the base mix by measuring the weight of a foam sample (to the nearest 0.1g) in a container of a known volume (to the nearest 1.0 ml).

Figure 3.6: Foam generator

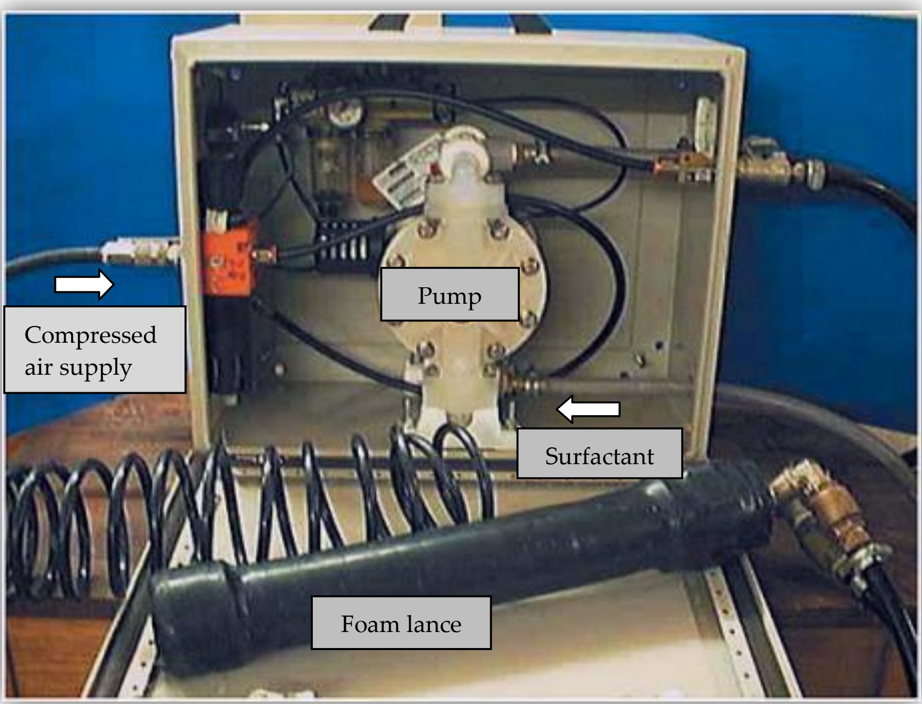


Figure 3.7: The interior of foam generator

Figure 3.8: Foam discharged from the lance

Figure 3.9: Foam in a jar for density check

3.6 SPECIMEN PREPARATION

In this study, foamed concrete production in the laboratory was carried out following two methods: using a rotary drum (free-falling action) mixer and Hobart mixer (Figures 3.10 and 3.11). The choice depends on the volume of foamed concrete produced. However, the mixing sequences were the same in both methods. The rotary drum, which has the capacity of 25 litres, is used for production of bigger volume, while the Hobart mixer is suitable for smaller volume of foamed concrete not greater than 3.5 litres. The Hobart mixer moves in planetary action.

As there is no standard for foamed concrete preparation, the mixing was carried out as described by Kearsley (1996). The dry materials, that is, cement and fillers (fine aggregates and/or other fillers), were combined in the mixer for half a minute. The total quantity of water was then added and mixed with the dry materials for approximately four minutes until a homogeneous base mix was obtained. The preformed foam was then produced by the foam generator and the approximate quantity (calculated by the mix proportions) added to the mix immediately after preparation. The mix was combined for at least two minutes until all foam was uniformly distributed and incorporated, which is noticeable during mixing.

The plastic density of the foamed concrete was then measured in accordance with BS EN 12350-611 by weighing a foamed concrete sample in a pre-weighed container of a known volume. A tolerance on plastic density was set at ± 50 kg/m^3 of the target value, which is typical of industry practice for foamed concrete production. If the density was higher, additional foam was prepared and added incrementally until a density within the accepted range was achieved. However, mixes with densities lower than the range of acceptable values were discarded and the whole mixing process was repeated.

The forms used in this study were lined with domestic plastic 'cling' film as foamed concrete was found to adhere strongly to the mould surface, irrespective of the type and quantity of release agent used. No compaction was provided to prevent the collapse of the preformed foam. The exposed as-cast surface of the specimens was immediately covered with cling film to minimise water loss. After de-moulding at 24h, the specimens were sealed-cured (that is, wrapped in 'cling' film) and stored at 20 ± 2 ^{0}C until testing.

Figure 3.10: Mixing sequence in rotary drum mixer

Figure 3.11: Mixing sequence in Hobart mixer which moves in planetary action

3.7 STANDARD PROCEDURE

There are standard procedures which are common to all studies. These are tests for plastic density, curing, consistency and compressive strength. However, procedures which are specific to each study are described in each study.

3.7.1 Plastic density

Plastic density of foamed concrete is measured in accordance to BS EN 12350 – 6 and values within ± 50 kg/m³ of the target density is accepted; foamed concrete outside these values were discarded and repeated. This was done by filling a container of known mass and volume with foamed concrete (Figure 3.12). The excess amount at the top of the container was removed and levelled of using a trowel or float without compaction. The container was weighed to obtain the plastic density using the following equation:

$$\rho_m = \frac{M_2 - M_1}{V} \qquad \textit{Equation 3.3}$$

Where:

ρ_m = target plastic density, kg/m³

$M2$ = combined mass of container and sample, kg

$M1$ = mass of empty container, kg

V = volume of container, m³

The stability of foam can be observed visually. However, to examine volume stability, foamed concrete is poured into Perspex cylinders of 300 mm and 500 mm tall with 75 mm diameter without compaction (Figure 3.13). Any collapse or segregation can be observed visually and by measuring the height of the specimens when the specimens are demoulded after 24 hours. The specimens are then wrapped in 'cling' film and left to cure at room temperature (Figure 3.14). They are split open and the bubble structures are examined for any possible segregation.

3.7.2 Curing

A typical definition of curing (BS 8110, 1997) is 'the process of preventing the loss of moisture from the concrete whilst maintaining a satisfactory temperature regime'. The need for curing concrete has been recognized since the inception of concrete. Although methods of curing for conventional concretes have been established, the curing regime for foamed concrete is still being explored. Following extensive research by Kearsley (1996 and 1999), the highest strengths were obtained on specimens cured at 50 ^{0}C and on specimens sealed in plastic bags and held at a constant temperature of 22 ^{0}C. Hence, the curing regime adopted in this study is sealed curing that is wrapped in cling film and stored in plastic bags at constant temperature of 22 ^{0}C as this is the most common curing regime adopted by other researchers (Jones and McCarthy, 2004, 2005a, 2005b, Kearsley and Wainwright, 2000a, 2000b, 2001a, 2001b, Wee et al., 2006).

Curing was done by wrapping all specimens which had been de-moulded after 24 hours. Wrapping was done using 'cling film' (Figure 3.15). The specimens were then placed in a controlled dry room where the temperature was maintained at 20 ± 2ºC until testing.

Figure 3.12: Density check for foamed concrete

Figure 3.13: Foamed concrete freshly poured into cylinder

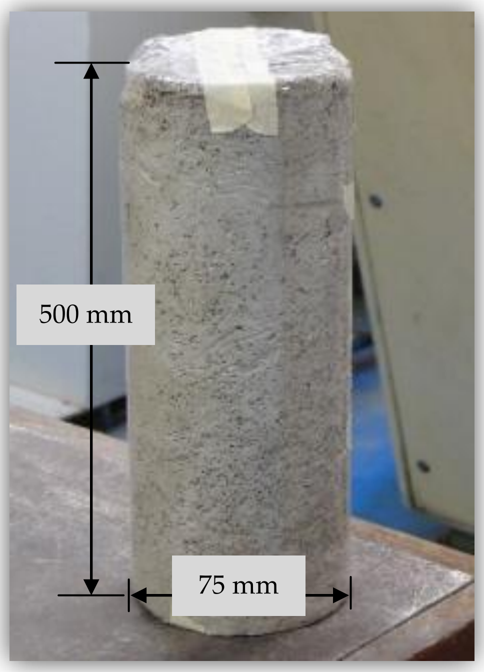


Figure 3.14: After 24 hours, foamed concrete demoulded and wrapped in 'cling film'

Figure 3.15: Cubes covered with 'cling film' and placed at room temperature 20 ± 2^{0}C before demoulding

3.7.3 Consistence

Workability or 'flowability' can also be assessed from the efflux time of a litre sample through a modified Marsh cone. Marsh cone is a workability test used for specification and quality control of cement pastes and grouts. It is developed from V-funnel equipment which is used to test flowability of high flow concrete (Roussel and Le Roy, 2005). Dundee Marsh cone was modified by Dhir et al. (1999a, cited by Jones et al., 2003) in terms of orifice diameter and the volume of efflux. The diameter was increased from 8 mm to 12.5 mm for use with foamed concrete, to take into account the presence of sand fine aggregates particles and the volume of efflux was increased to 1 litre from 200 ml.

The procedure is as follows:

1. A Marsh cone is attached to a stand (Figure 3.16). The dimensions of the modified Marsh cone are as shown in Figure 3.17.

2. Closing the nozzle, the cone was filled with 1.5 litres of sample and the time was measured for 1 litre of foamed concrete to flow through the constricted orifice.

The flow time and behaviour are classified as in Table 3.5 (Jones et al., 2003)

Figure 3.16: Modified Marsh cone

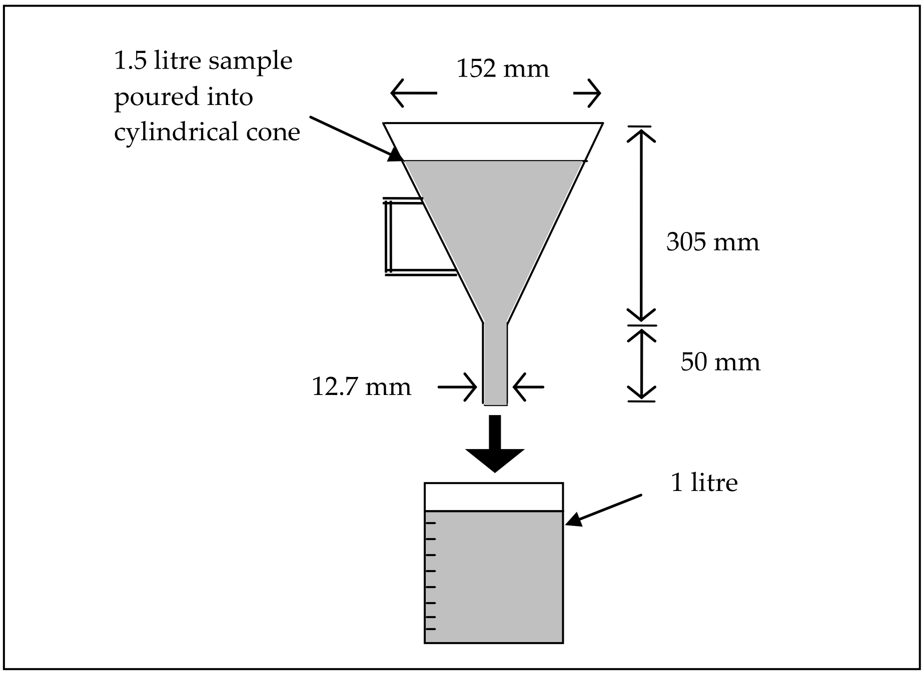


Figure 3.17: Dimensions of modified Marsh cone

Table 3.5: Classification of foamed concrete flow ((Jones et al., 2003)

Main Class	Flow Rate	Sub Class	Description of flow
1	1 litre in < 1 minute	A	Constant flow
2	1 litre in > 1 minute	B	Interrupted flow
3	0.5 litres <efflux< 1 litre	C	Completing of flow after gentle tamping
4	Efflux < 0.5 litres		
5	No flow		

3.5 CUBE STRENGTH

Compressive strength can be measured at 7, 28 and/or 56 days essentially in accordance with BS 1881: Part 1 16: 1953. Disposable polystyrene moulds are widely used for foamed concrete: these can be supplied with lids so that a specimen can be left in the mould until immediately prior to testing. Steel moulds can be used but they should be lined with a non-stick plastic film. Mould release oil should not be allowed to come into contact with the foamed concrete because it can affect the properties of the concrete.

The specimens should be covered and, ideally, left undisturbed for least 3 days to prevent damage by movement and demoulding. After demoulding the cubes should be immediately wrapped in an air and watertight film ('cling film') and stored at 20 ± 2^0C in plastic bags (sealed curing).

Compressive Strength Test

The compressive strength of foamed concrete is no different to the compressive strength of standard concrete as in it is affected by the density, cement content and the w/c ratio. The density of the foam can have an influence on the ultimate strength, because when more foam is added the compressive strength is affected adversely. Sealed cured cubes of size 100 X 100 mm were tested for compressive strength for 7 and 28 days in accordance with BS EN 12390-3. The tests were done with AVERY loading frame, where the cubes were placed centrally under the loading plates and positioned to have even surfaces in contact with the loading plates (Figure 3.18). The rate of loading was gradually increased manually during testing until cube failure. The failure load was recorded and cube strength was calculated using equation 3.4. The compressive strength of the cube was calculated to the nearest 0.1 N/mm^2.

Two specimens were tested at each age.

$$\text{Cube strength} = \frac{\text{Load at failure}}{\text{Cross sectional area of cube}} = \text{to the nearest 0.1 N/mm}^2 \qquad \textit{Equation 3.4}$$

Figure 3.18: Compressive strength test on foamed concrete cube

CHAPTER 4: PERFORMANCE OF MODEL STRUCTURAL ELEMENT

4.1 INTRODUCTION

The use of foamed concrete has been established for underground applications such as trench reinstatement and void fillings. While it is acknowledged that foamed concrete has low self-weight and a rheology that is flowing, self-levelling and self-compacting, it is also recognized as having excellent fire and thermal resistance. Given its advantages of being economic, simple to use and environmentally sustainable, the use of foamed concrete should not be confined to underground use. However, the strength of foamed concrete with densities between 400 to 1600 kg/m^3 was recorded to be between 1 to 10 kN/m^3 (Dijk, 1991; BCA, 1994, Jones and McCarthy, 2005b). This low strength had caused foamed concrete to be disregarded as structural material. Researches over the past decade have sought to increase the strength of foamed concrete. Several developments had been made, for example using different surfactants, cement types, design mixes, methods and addition of fibres (Kearsley and Visagie, 1999; Jones and McCarthy, 2005b; Nambiar and Ramamurthy, 2006b).

The possibility of using foamed concrete in structural applications has been widely discussed and studied (Jones and McCarthy, 2005, BRE report IP 12/04, Jumaat et al., 2009). Jones and McCarthy (2005b) concluded that foamed concrete has properties that suggest that it is practicable for use as a structural material. In their experiments using different design mixes incorporating coarse fly ash, the strength of foamed concrete at 28 days was 25kN/m^2 for foamed concrete of 1600 kg/m^3 density. Higher density and longer curing period (at 56 days) produced comparably higher strength. Additionally, full-scale pilot tests using steel reinforcement and polypropylene fibres in the foamed concrete beams indicated satisfactory behaviour in their short-term experiments. However, it transpired that the addition of fibres had caused some rheological difficulties in the foamed concrete. Consequently, it was suggested that a more innovative approach should be taken to application and reinforcement materials and methods (Jones and McCarthy, 2005b). One such approach undertaken by Jumaat et al. (2009) experimented with the use of oil palm shells in foamed concrete of 1600 kg/m^3 density and recorded compressive strength of 25kN/m^2. Full-scale oil palm shell foamed concrete beams using steel reinforcement were also tested.

Adopting the perspective that foamed concrete is potentially viable for use as a structural material, the current study determined to assess the behaviour of reinforced foamed concrete in a more practical way. The method adopted was pre-stressing, based on different approaches used in previous researches (Jones and McCarthy, 2005b; Jumaat et al. 2009). Unlike the normal reinforcement method, pre-stressing in normal concrete is achieved by inducing compressive stresses before loads are applied in order to counteract anticipated tensile stresses imposed in the member during the service. Compressive stresses are induced in pre-stressed concrete either by pre-tensioning or post-tensioning the steel reinforcement. Pre-tensioning is a process which can be done at a pre-cast manufacturing facility and post-tensioning can be performed on the jobsite in cast-in-place applications. In post-tensioned examples, the behaviour of the beam is expected to be observable when tension is applied; hence this method is adopted. In contrast to normal post-tensioned concrete beam, where the materials used are typically high strength steel strands or bars, the material used in this study was pultruded glass-fibre reinforced plastic rods. This was selected because of its lightness and perceived ease of bond with foamed concrete of similar lightness in density.

The overall aim of the study was to investigate the feasibility of producing post-tensioned foamed concrete sections in terms of practicality and engineering properties. The behaviour investigated was intended to assess the possibility that post-tensioning may improve the serviceability limit and reducing deflection. This is in accordance to BS 8110 and Eurocode 2 for deflections and cracking, where any deflection is adequately small, equivalent to length/250 and minimum crack widths.

4.2 MATERIALS, EXPERIMENTAL PROGRAMMES AND METHODOLOGY

4.2.1 Introduction

The overall aim of this study was to improve the serviceability limit of foamed concrete beams by method of post-tensioning as shown in the conceptual graph in Figure 4.1. In this graph, the current typical behaviour of foamed concrete beam is illustrated by line P1, where, at small load, the deflection is high. Improvement in serviceability for deflection by post-tensioning was intended to decrease deflection from point A to point B, and ideally to point C, in line P3. In another view, higher loads will be possible without exceeding the serviceability limit.

Full-scale foamed concrete beams reinforced with polypropylene fibres showed an improvement in deflection (Jones and McCarthy, 2005b). Adopting similar mix design and beam dimensions, this experiment used a different method of reinforcement. In this study, two beams were post-tensioned using a glass-fibre reinforced polymer (GFRP) rod. Compared to carbon steel, this material was more suitable because foamed concrete has relatively poor carbonation resistance (Jones and McCarthy, 2005b). The density of GFRP was near to the density of foamed concrete. Beam 1 was tensioned at the bottom and beam 2 was tensioned at both the top and bottom.

The target plastic density was 1400 kg/m^3 with 600 kg/m^3 cement content and 0.35 w/c ratio. This density was chosen because it was found that 1400 kg/m^3 is the minimum density at which foamed concrete with coarse fly ash (FA$_c$) filler could be used in structural elements (Jones and McCarthy, 2005b).

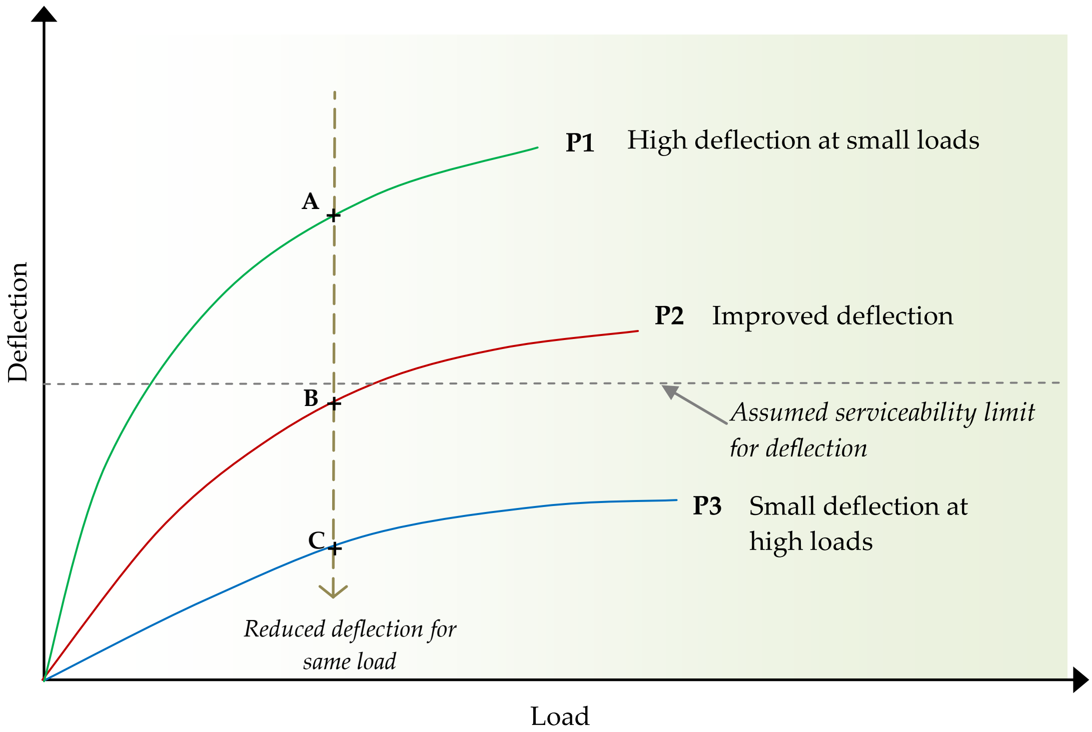


Figure 4.1: Hypothetical improvement to serviceability limit of foamed concrete beam.

4.2.2 Constituent Materials

1. Portland cement (CEM I 42.5N conforming to BS EN 197-1: 2000) was the cement employed.

2. The filler was 100 per cent coarse fly ash (FA_c) with a 45μm sieve retention of 36.0% and conforming to BS 3892-2/ BS EN 450 and ASTM C 618-94a Class F.

3. The surfactant was a synthetic type foaming agent which was commercially available. The dilution was 6% aqueous solution which produced foamed to a density of 50 kg/m^3.

4. Superplasticiser conforming to BS EN 934-2.8. This superplasticiser was used because at 0.35 w/c ratio, the mix was less workable to fill up the formwork.

5. Pultruded glass-fibre reinforced polymer (GFRP) rod the size of which was 12 mm in diameter. The length was longer than beam length (2 m) which allowed for post-tensioning. The properties of the glass-fibre reinforced polymer are described in Table 4.1.

4.2.3 Formwork preparation

The dimensions of the beams were 200 mm by 300 mm (height) and 2000 mm length, as shown in Figure 4.2. These were carefully constructed for easy reassembling. After beam 1 was demoulded, the same formwork was used for beam 2, as shown in Figure 4.3.

A single GFRP rod was positioned in the centre at 20 mm from the bottom of beam 1 and beam 2. These were held in place using polystyrene spacers. An additional rod for beam 2 was placed at 20 mm from the top level of the beam.

For both beams, two inverted-U steel bars were cast in the beam for ease of transportation around the laboratory areas. The positions of the bars were 414 mm from both ends (Figure 4.4). These were points of zero bending moment (point of contraflexure).

Table 4.1: Glass fibre reinforced plastics, GFRP

	Properties	Value
1.	Flexural strength	275-700 MN/m^2
2.	Flexural modulus	14-34 GN/m^2
3.	Tensile strength	200-550 MN/m^2
4.	Tensile modulus	14 - 31 GN/m^2
5.	Compressive strength	96-206 MN/m^2
6.	Izod impact strength	50 -100 ft. lb.
7.	Fire retardancy	Surface spread of flame (BS 476) to Class 1 or Class 2 can be attained.
8.	Density	1700 - 1900 kg/m^3
9.	Water absorption	0.5 - 2%
10.	Barcol hardness	40 - 70
11.	Specific heat	940 J/kg K
12.	Thermal conductivity	0.35 W/m K
13.	Co-efficient of thermal expansion	7.2×10^{-6} / K
14.	Heat Distortion Temperature	100 - 200^0C

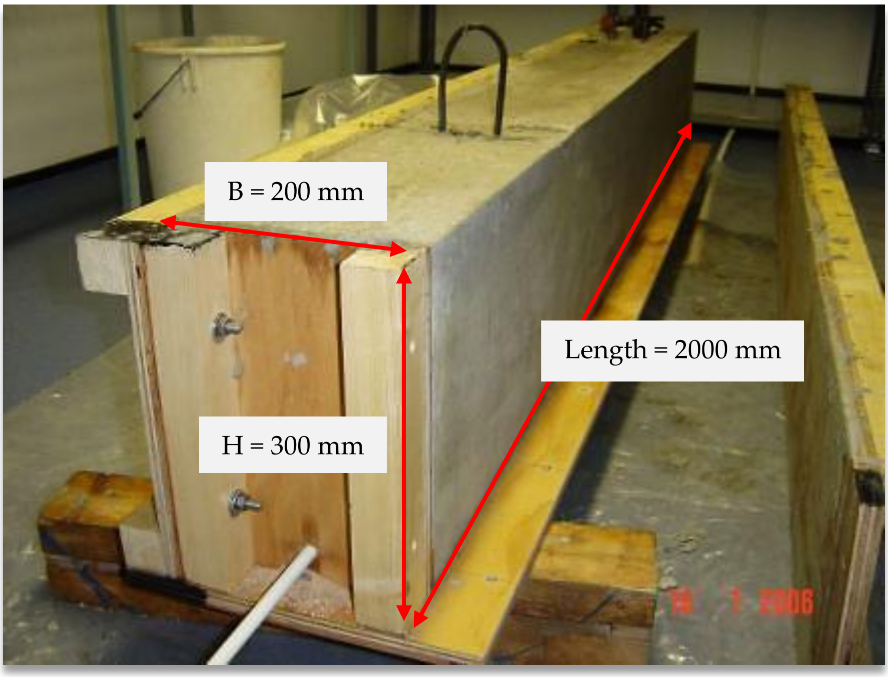


Figure 4.2: Dimensions of beam 1

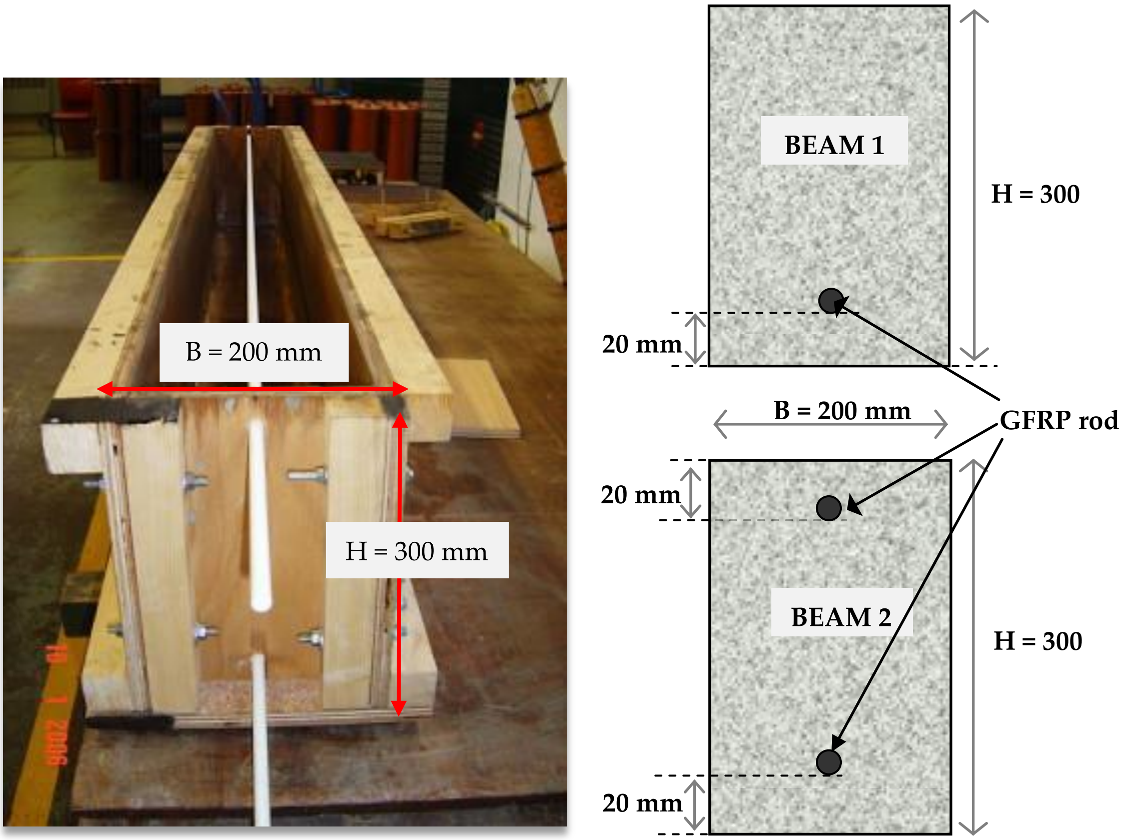


Figure 4.3: Dimensions of beam 2

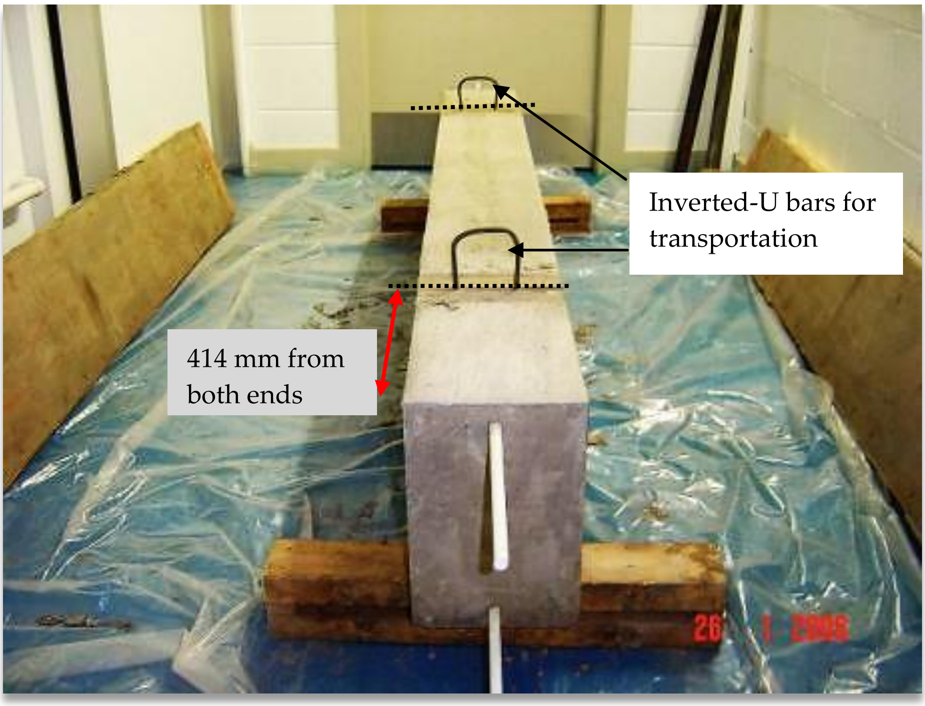


Figure 4.4: Position of inverted U-bars

Figure 4.5: Foamed concrete mixed in a standard inclined rotating mixer

4.2.4 Beam mix design

As described previously, there are no standard methods for proportioning foamed concrete. The method employed in this study used the method developed by the University of Dundee, where the target density was the prime design criterion. In this study, the target density was 1400 kg/m^3 with 0.35 w/c ratio. This calculation was based on the assumption that, for given cement content and w/c ratio, the sum of solids (cement and filler) and water content was equal to the target plastic value.

Foamed concrete was produced in the laboratory using a standard inclined rotating (free-falling) drum mixer (Figure 4.5). The base mix was first produced by mixing coarse fly ash (FA_c), cements and water as shown in Figure 4.6. The preformed foam was added to the base mix and the mixing continued until a uniform consistency was achieved (Figure 4.7). Next, the plastic density was measured in accordance with BS EN 12350-611 by weighing a foamed concrete sample in a pre-weighed container of a known volume. A tolerance on plastic density was set at ± 50 kg/m^3 of the target value as being acceptable.

The specimens were then cast in the formwork. Since the capacity of the inclined rotating drum was only 25 litres, the foamed concrete was batched continuously. For each batch, the plastic density was weighed accordingly. After the formwork had been completely filled, it was covered with plastic sheets to prevent early dehydration, as shown in Figure 4.8. The specimen was stored at 20^0C until de-moulding.

The beam was de-moulded after 10 days and wrapped in 'cling' film, it was then left in the same location at 20^0C until testing (Figure 4.9)

Figure 4.6: Base mix in rotary mixer

Figure 4.7: Foam added to base mix

Figure 4.8: Beam covered in plastic sheet after cast

Figure 4.9: Beam wrapped in ‘cling’ film after formwork removal

4.2.5 Preparation for post-tensioned

After 28 days, the beams were taken out of the temperature controlled room. As shown in figure 4.10, each beam was coated with white paint which allowed for clear visual examination of cracks or any change in behaviour. Next, demec studs were glued onto the beam in 3 groups, namely, at the middle and near both ends of the beam (Figure 4.11). The studs within each group were sited 50 mm from each other. The application of the studs helped in examining dimensions for changes. Three dial gauges were positioned at 'critical' points to note any change for possible sagging or hogging of the beams (Figure 4.12). One end of the protruded rods was fixed, as shown in Figure 4.13, whilst at the other end; the rod was mechanically pulled out to create tension in the beam (Figure 4.14). After tension was introduced, changes in beam 1 were noted from the readings in the dial gauges and appearance of fine cracks. The same procedure was repeated in beam 2. However, as there were two rods in beam 2, tension was created accordingly in both bottom and top rod. After each rod had been tensioned, the changes and readings were recorded. The beams were then tested at two-point loads, as shown in Figure 4.15.

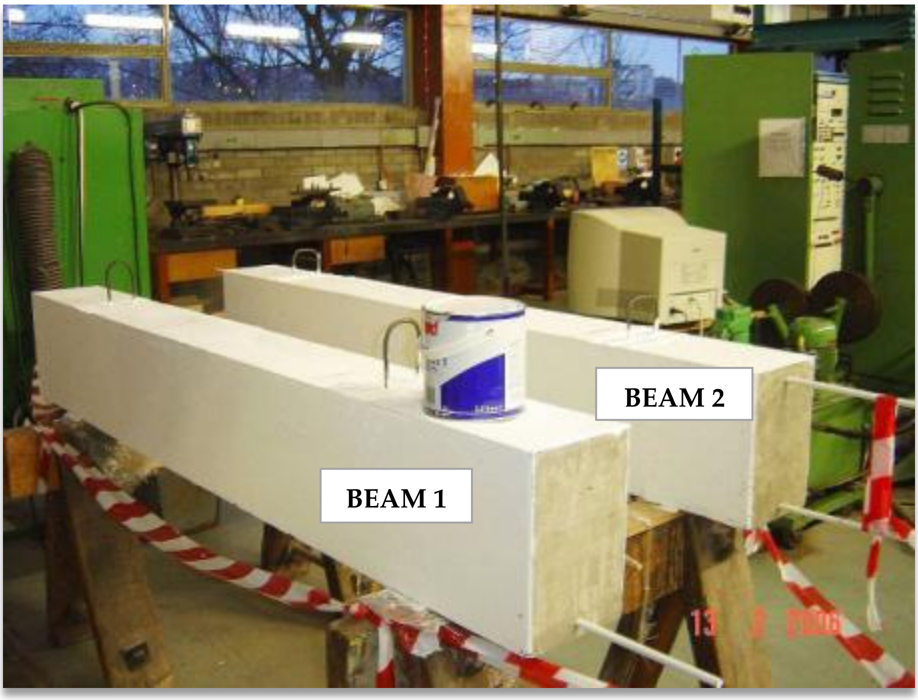


Figure 4.10: Beam 1 and beam 2 coated with white paint

Figure 4.11: Demec studs glued in positions

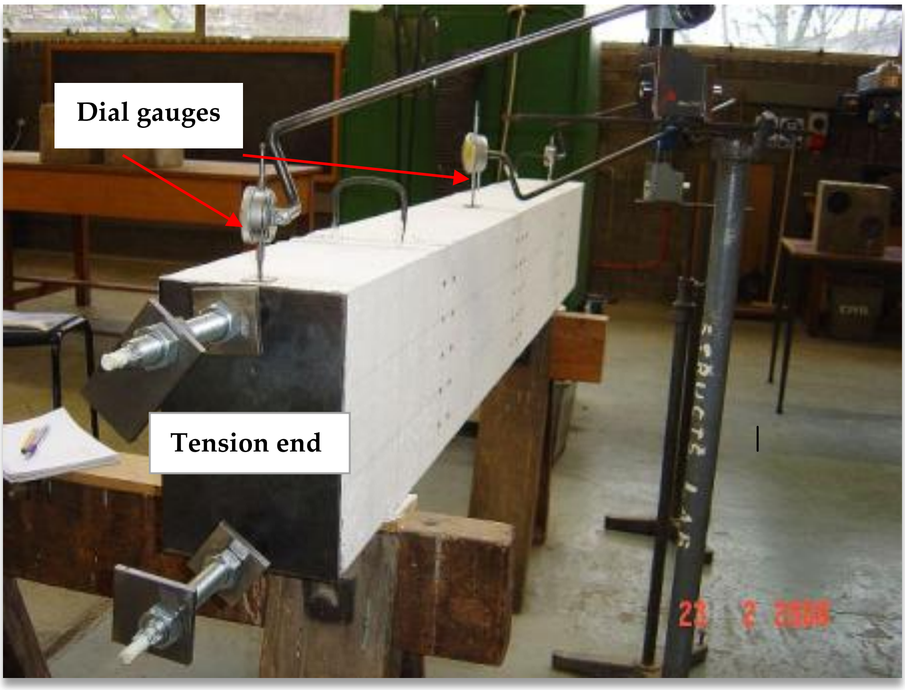


Figure 4.12: Three dial gauges positioned at 'critical' points

Figure 4.13: Close-up detail of fixed end

Figure 4.14: Close-up detail of tensioned end

Figure 4.15: Beam prepared to be tested

Figure 4.16: Cracks propagated

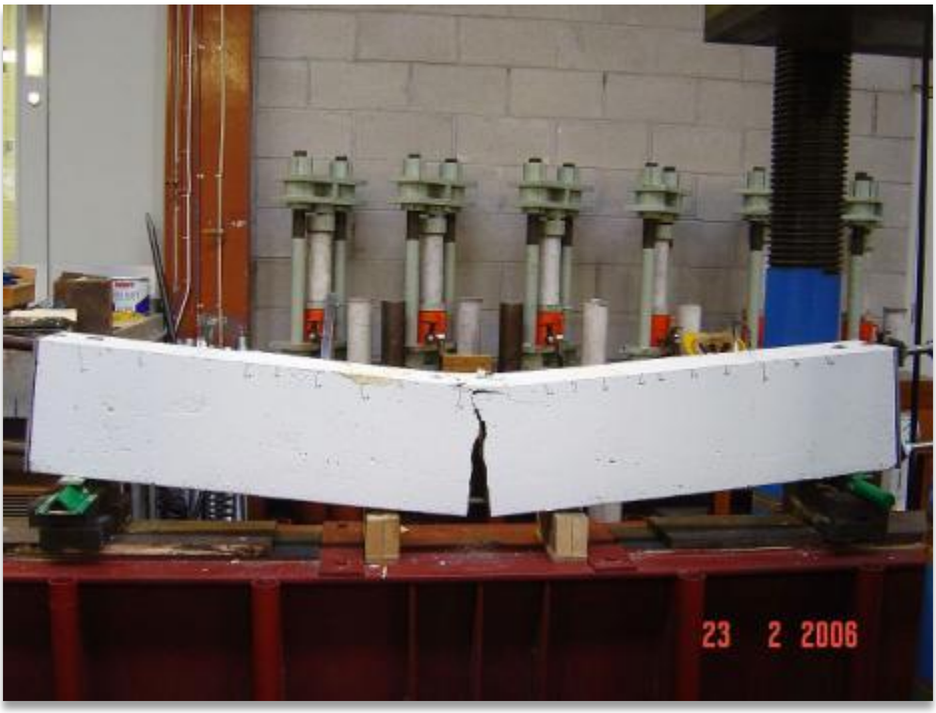


Figure 4.17: Tested Beam - front view

Figure 4.18: The reinforcement creep and did not sustain the added tension in the beam

Table 4.2: Compressive strength for 5 mixes

		Compressive strength (N/mm²)		
	Actual plastic density (kg/m³)	7d	14d	28d
Mix 1	1425.0	11.0	17.4	21.1
Mix 2	1420.0	8.0	20.5	20.0
Mix 3	1420.0	10.0	17.6	21.0
Mix 4	1415.0	9.5	13.9	20.0
Mix 5	1395.0	7.6	11.5	19.0

4.3 RESULTS

4.3.1 Compressive strength

Five mixes were batched which made up the beam. For each mix, the density was weighed and compressive strength tests were on each mix. The acceptable mixes are shown in Table 4.2. From this table, there was a small variation within the target density of 1400 kg/m^3. The average compressive strength for 28 days was 20.2 N/mm^2.

4.3.2 Effect of added tension

After tension was introduced, changes in the beam were noted from the readings in the dial gauges and appearance of fine cracks. After each rod had been tensioned, the changes and readings were recorded. It is shown in Table 4.3 that when stress was added, there were displacements in the beam. The two ends showed negative displacements; -0.36 mm and - 0.18 mm, which indicated the ends displaced downwards and the centre beam displaced upwards, as indicated by the positive displacement, 0.19 mm.

Table 4.4 showed the displacement readings when tension was added consecutively by mechanically pulling out the bottom rod and the top rod. When tension was added in the bottom rod, in reading Set 1, the displacements were negative in point A and C which indicated the beam hogged. In reading Set 2 when the top tension was added, there was a negative displacement in point B, which implied that the beam sagged. Consecutive readings in Set 3 (bottom) and 4 (top) suggested that the beam behaved in expected manner; hogging and sagging accordingly.

4.3.3 Two point load test

1. There was high deflection on 1st crack.
2. The foamed concrete beam did not sustain the added tension because of the reinforcement creep (Figure 4.18).

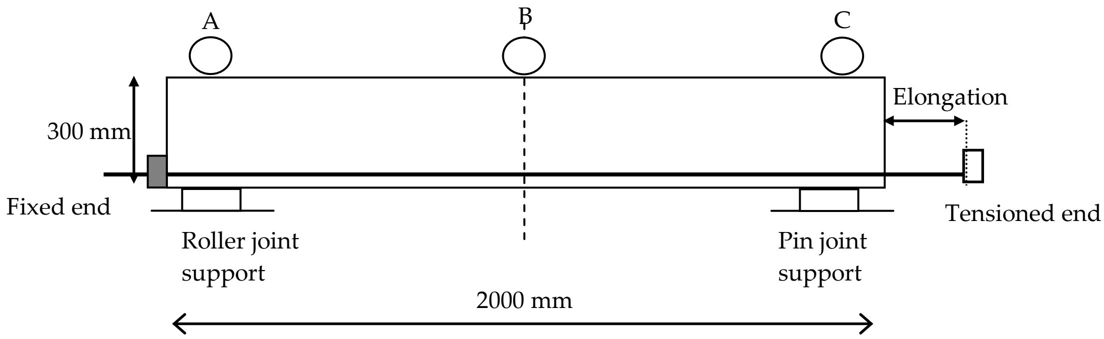


Table 4.3: Displacement readings with added tension (mm)

	A	B	C
1	0	0	0
2	-0.04	0.01	0
3	-0.05	0.04	-0.02
4	-0.11	0.12	-0.02
5	-0.11	0.19	-0.05
6	-0.125	0.23	-0.08
7	-0.12	0.28	-0.11
8	-0.19	0.30	-0.12
9	-0.20	0.30	-0.125
10	-0.24	0.32	-0.13
11	-0.25	0.20	-0.15
12	-0.31	0.19	-0.23
13	-0.32	0.20	-0.11
14	-0.33	0.21	-0.11
15	-0.34	0.20	-0.13
16	-0.34	0.20	-0.11
17	-0.36	0.21	-0.15
18	**-0.36**	**0.19**	**-0.18**

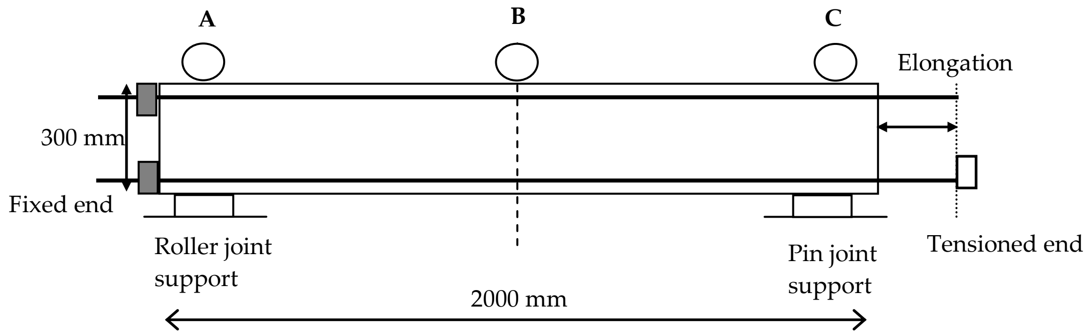


Table 4.4: Displacement readings when tension added at top and bottom

	A	B	C
Reading Set 1 - bottom tension added			
1	0	0	0
2	-0.04	0.09	-0.04
3	-0.06	0.095	-0.1
4	-0.1	0.1	-0.12
5	-0.12	0.1	-0.14
6	**-0.13**	**0.1**	**-0.14**
Reading Set 2 - top tension added			
1	0	0	0
2	0	-0.003	0
3	0	-0.003	0
4	0.015	-0.003	0.01
5	0.02	-0.002	0.015
6	**0.025**	**-0.002**	**0.01**
Reading Set 3 - bottom tension added			
1	0	0	0
2	-0.01	0	0.01
3	**-0.01**	**0**	**0.01**
Reading Set 4 - top tension added			
1	0	0	0
2	0	0	0
3	**0.005**	**0**	**0.02**

4.4 SUMMARY OF RESULTS

1. The average compressive strength of foamed concrete was 20.2 N/mm^2 at 28 days. With the use of 100 % FA_c as filler, the compressive strength of foamed concrete cubes was expected to gain more than 25 N/mm^2 at longer curing days.
2. Manufactured post-tensioned was selected because of the ability to control the amount of stress and to prevent preload fracture. The approach was able to control sagging and hogging in the beam.
3. The foamed concrete beam responded to the tension added, thus shown in the displacement readings, where the hogging and sagging corresponded to the tension added.
4. There was high deflection on the first crack due to the creep by the GFRP rod. This unsatisfactory outcome was related to reinforcement problem.

CHAPTER 5: RHEOLOGY

5.1. INTRODUCTION

Foamed concrete is known to have low density 400 - 1600 kg/m^3. It does not behave like conventional concrete due to its individual properties, in particular, the ability to self-compact. Dhir et al. (1999) found that the yield values of foamed concrete were all less than 2 Nm, which indicates self-flowing behaviour. As a result, foamed concrete acts more like a fluid. In addition to its self-compacting ability, foamed concrete has the further advantages of being self-levelling, of transferring load and being easy to re-excavate. All cement–based materials depend on rheology which implies pumping, spreading, moulding and compaction. Many examples exist of foamed concrete being pumped over considerable distances and of foamed concrete being used as reinstatement material (Aldridge, 2000; Basiurski, 2000).
(http://www.foamedconcrete.co.uk/news1.php, accessed 20th January 2011)

The Highways Agency and Transport Research Laboratory (2001) stated that the workability of foamed concrete increased with additional increases in the water:cement (w/c) ratio and by increasing the dosage of superplasticiser. This literature also noted that concrete formed from a protein-based surfactant has a much shorter flow time, indicative of a much lower plastic viscosity, and was prone to segregation. Jones and McCarthy (2005) found that foamed concrete using low-lime coal fly ash mixes was less viscous than sand mixes. Although Nambiar and Ramamurthy (2006) have reported that the flow of foamed concrete mixes was reduced with an increase in foam volume, and that the flow reduced steeply with reduction in design density, these findings have yet to be verified by other studies.

Foamed concrete has been widely used for underground works such as backfilling, soil stabilising and trench reinstatements. These can involve pumping concrete over long distances, filling in gaps and deep orifices, moulding, spreading and self-levelling areas. For these applications, the consistency in rheological properties is crucial in predicting the behaviour of foamed concrete to avoid segregation, premature setting, and the inability to achieve self-levelling. Rheological properties in the fresh state of foamed concrete play a critical role in the development of foamed concrete in the hardened state.

These rheological properties, namely, yield stress and plastic viscosity, are also influenced by the mix design – densities, w/c ratio and the constituent materials - cement type, fillers and surfactants that produce the foam. Yield stress is the minimum stress required to initiate flow and plastic viscosity is the measure of the internal resistance for fluid to flow. The rheological properties can also be related to the microstructure and the instability. Three significant themes that emerged in the study of foamed concrete and rheology are:

1. the empirical values of yield stress and plastic viscosity of the mixes;
2. the different behaviour influenced by design mixes and materials; and
3. the relationship between rheological properties, microstructure and instability.

These three themes formed the basis for investigation of the characteristics of foamed concrete in this study. It was noted that the empirical results were not straightforward to obtain. This made it very difficult to relate results to similar tests (Ferraris, 1999).

5.2 MATERIALS, EXPERIMENTAL PROGRAMMES AND METHODOLOGY

5.2.1 Introduction

Foamed concrete is far more Bingham in nature than Newtonian or thixotropic due to the build-up of structure within the materials (McCarthy, 2005). The air content changes as the w/c ratio and the density change; an increase in w/c ratio decreases the air content. In the same way, the air content decreases with increase in density. Significant changes to the rheological behaviour were found when using different constituent materials (Jones and McCarthy, 2005b).

The overall aim of the current study was to investigate the rheological properties of foamed concrete in relation to varying the air content, varying the different constituents and varying the different proportions of the constituents. The effect of varying air content was investigated as it was found that, in cement-based materials, an increase in the air content (by increasing the amount of air-entraining agent) had resulted in changes to the plastic viscosity and the yield stress (Chia and Zhang, 2004; Seabra et al., 2007).

In the current study, there were two groups of tests. In the first group, one set of constituent materials was used in different densities and w/c ratios. The foamed concrete densities were 600 kg/m^3, 1000 kg/m^3 and 1400 kg/m^3 at w/c ratio 0.4, 0.5 and 0.6. In the second group, five mixes of different proportions of the constituent materials at density 600 kg/m^3 with w/c ratio 0.40 to 0.80 and three mixes of density 1000 kg/m^3 at 0.40 to 0.80 w/c ratio.

Most of the tests employed to measure rheological properties are capable of testing a single parameter: the yield stress or plastic viscosity (Ferraris, 1999). The slump test is an example of single point test method which is commonly used as an indication of concrete workability. The slump value is related to yield stress and not comparable with any other rheological measures (Chia and Zhang, 2007; Roussel, 2007). The Marsh cone test is another single point test which relates measured flow time out of the cone to fluidity (Roussel, 2005). The Marsh cone test measures the plastic viscosity of the material.

Since foamed concrete behaves more Bingham-like in nature, the study of its rheological properties required two rheological parameters: yield stress and plastic viscosity. The method used in this current study was based on the widely known two-point test which was first introduced by Tattersall (1991) and further developed by Domone et al. (1999). The test equipment employed was the Brookfield viscometer, which was capable of measuring the viscosity of fluid (Figure 5.1). This technique used a rotating element inserted into the specimen and rotated at a constant velocity. The principle of measurement by the rotating viscometer utilised the rule that the rotating torque (the force to cause steady rotation) is proportional to the viscosity.

In addition to the Brookfield viscometer, the Dundee Marsh cone test was also briefly included in order to study the flowability of the second group of foamed concrete mixes. The method statement of the Dundee Marsh cone test was described in Chapter 3.

5.2.2 Constituent Materials

1. Ordinary Portland cement (CEM I 42.5N conforming to BS EN 197-1) was the cement employed in the Set 1. In Set 2, combinations of cementitious materials were selected. The total cementitious material was kept at 300 kg/m^3.

2. 'Fine' fly ash (FA_f) with a 45 μm sieve retention of 7.5%, loss on ignition (LOI) of 5.0% and conforming to BS EN 450.5 was used to replace CEM I 42.5N at 30% by mass fraction.

3. Metakaolin used as replacement for cement to a level of 20%. The high specific surface area of metakaolin was in the range of 4000m^2/kg to 12000m^2/kg.

4. The main filler was natural sand, fine aggregate (conforming to BS EN 12620:2002 with particles greater than 2.36 mm removed by sieving), although there was a variation in Set 2.

5. Coarse fly ash, FA_c with a 45μm sieve retention of 36.0% and conforming to BS 3892-2/ BS EN 450 and ASTM C 618-94a Class F was used as 50% and 100% replacement for sand.

6. The surfactants used in this study were protein-based which were commercially available. The dilution was 6% aqueous solution which produced foamed to a density of 50 kg/m^3.

7. The mixing water used conformed to BS EN 1008 Mixing water for concrete. In this study, the w/c ratio was varied from 0.40 to 0.60 in Set 1 and 0.40 to 0.6 in Set 2.

5.2.3 Experimental Programme

There were two main sets of experiments: Set 1 and Set 2 (Figure 5.1). In Set 1, a set of consistent constituent materials were used and combinations of cement and filler types were studied in Set 2. There were variations in densities and w/c ratios. The densities were 600 kg/m^3, 1000 kg/m^3 and 1400 kg/m^3 and the w/c ratios were 0.40, 0.50 and 0.60. For Set 2, only 2 densities were studied and wider range of w/c ratios.

5.2.3 Mix design

Foamed concrete was produced in a Hobart mixer. The Hobart mixer was the most suitable of the mixers tested because its mixing action generated the greatest mass transfer (interaction) between the base-mix and foam phases and also sufficient shearing action to generate suitable base-mix workability (Jones, 2000). Jones also stated that the use of mixers with greater vertical actions, such as helical or screw type may produce foamed concrete of higher strengths.

The base mix was first prepared by adding the sand or coarse fly ash with the cement and water until a homogeneous mix was achieved. Then preformed foam was added to the base mix and combined until fully incorporated and uniformly distributed. The plastic density of the foamed concrete was then measured in accordance with BS EN 12350-6. If the density was found to be higher than expected, additional foam was added incrementally. This was repeated until a density within the accepted range was achieved, which was within ±50 kg/m^3 of the target density. However, mixes with densities lower than the range of acceptable values were discarded and the whole mixing process repeated.

5.2.4 Brookfield Viscometer

As shown in Figure 5.2, the Brookfield viscometer was used in conjunction with a Helipath stand and a T-bar spindle. This eight-speed model has a square speed control knob with two numbers on each face. By moving the knob through two complete turns, this viscometer gave eight readings at increasing increments and then decreasing increments.

This type of Brookfield viscometer was a dial-reading type which notes the position of a pointer in relation to the rotating dial. The dial reading type (Figure 5.3) was suitable for most applications where samples are tested over a short period of time and a permanent detailed record of rheological behaviour was not required. Readings may be made intermittently when the pointer passes under the glass window or when reading is held and viscometer stopped. The Helipath stand was a motorised stand which slowly raises and lowers the viscometer (at a rate of 22 mm per minute) while a T-bar spindle rotates in the sample material. T-bar spindles were suitable for the measurement of non-flowing or slow-flowing materials such as pastes, gels and creams (Figure 5.4). The crossbar of the spindle thus continuously cuts into fresh material, describing a helical path through the sample as it rotates, thus eliminating the 'channelling' effect. By changing the rotational speed of the spindle, a range of readings was obtained. The values of yield stress and plastic viscosity were measured from the equation of the trendline obtained from the graphs of rotational speed (rpm) and the viscometer readings.

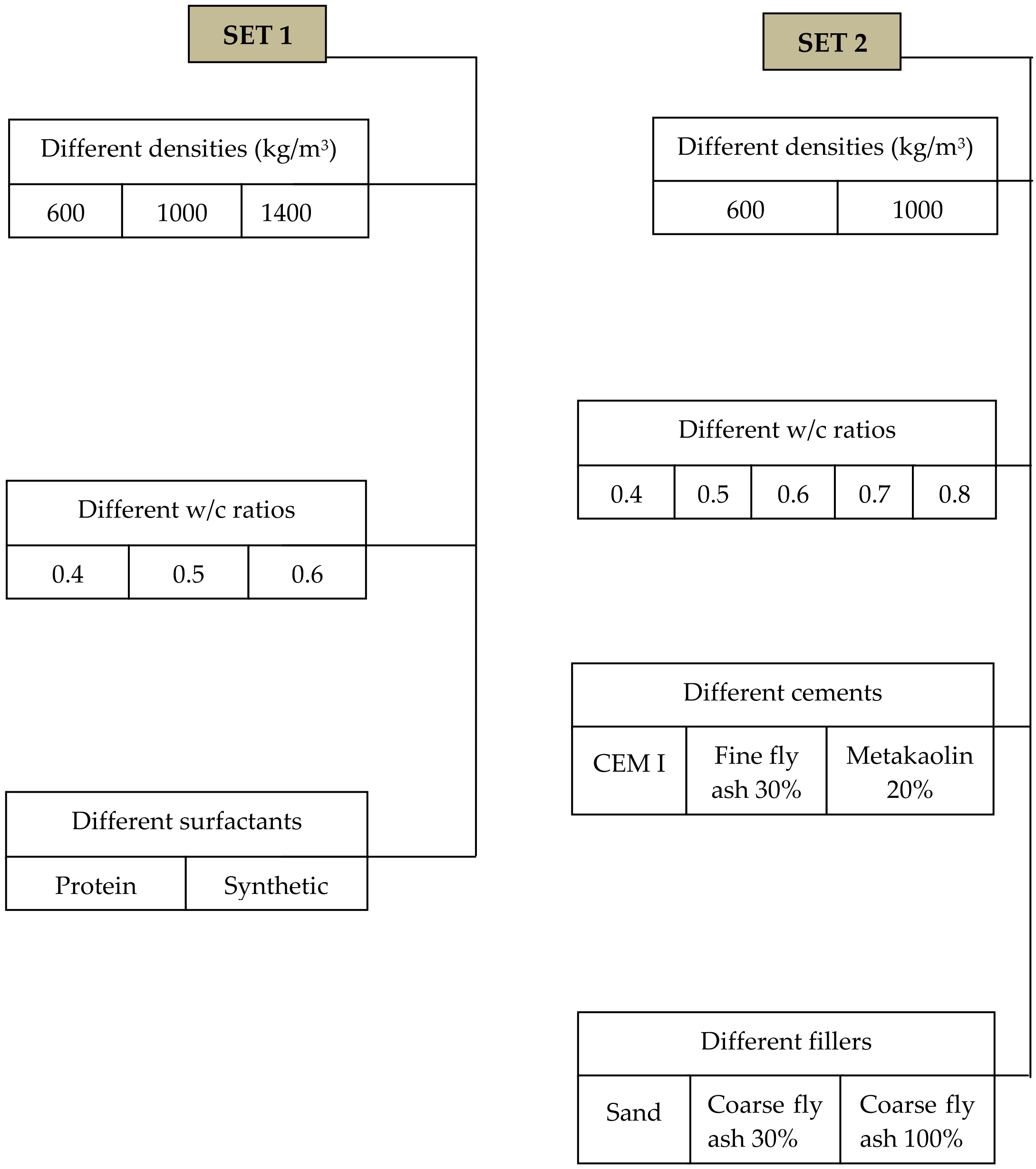


Figure 5.1: Experimental Programme

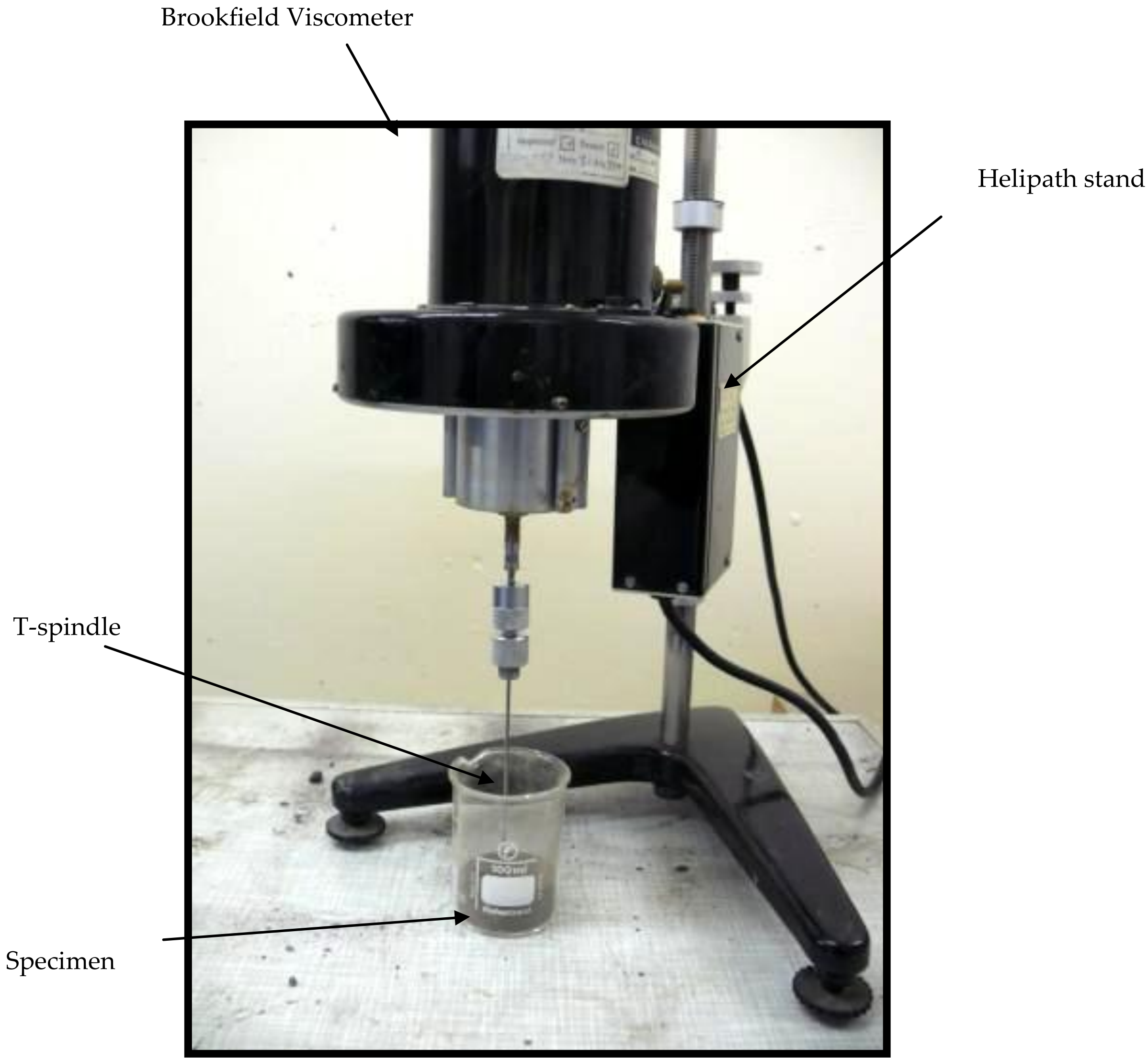


Figure 5.2: Brookfield Viscometer set

Figure 5.3: Brookfield Viscometer dial reading display

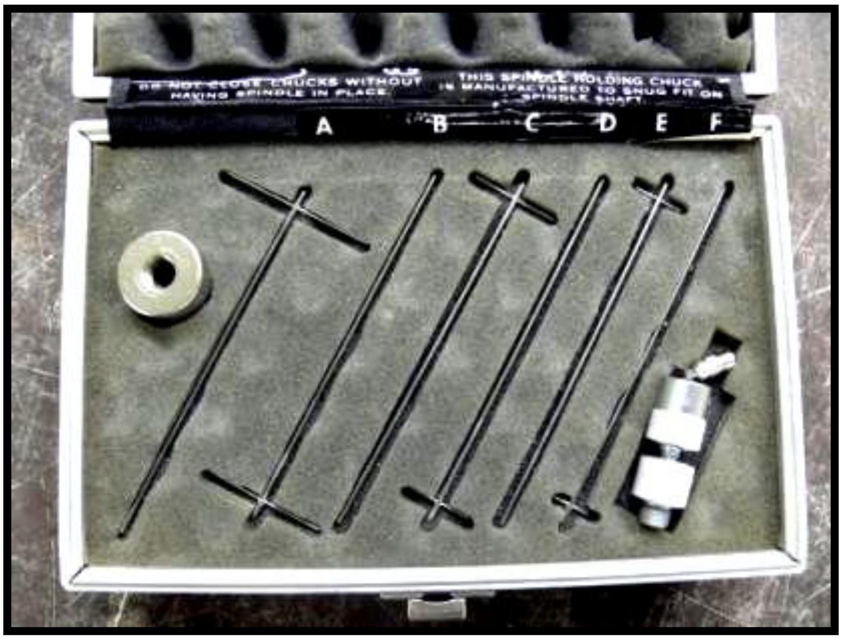


Figure 5.4: A set of spindles

Method Statement for using the Brookfield Viscometer

1. Set up the Brookfield viscometer as shown in Figure 5.2.

2. Pour the freshly mixed foamed concrete into a 100 ml plastic beaker to half fill the container.

3. Place the beaker under the Brookfield viscometer with the spindle positioned at the centre of the beaker.

4. Position the spindle in the centre to prevent the spindle from leaving the concrete or reaching the base of the beaker. This was done by adjusting the stopper prior to starting.

5. The spindle rotated in an upward and downward movement. Readings were taken every 30 seconds and repeated 3 times for each speed.

6. The spindle speed was increased at the preset increment; the range was from 0.5 to 100 revolutions per minute. Step 5 was repeated for each speed.

7. The readings were tabulated and plotted in a line graph. The axes for the graph were shear stress values (torque) for the x-axis and rate of shear values (rotational speed) for the y-axis (Figure 5.5). Using the best fit line drawn through all the corresponding shear stress values (torque) against rate of shear values, values of plastic viscosity (slope angle) and yield stress (intercept x-axis) can be obtained (Tattersall, 1991).

   An example of the calculation of yield stress and plastic viscosity for density 600 kg/m^3 at w/c 0.5 is shown in Figure 5.6. When the results are plotted a best fit line is drawn through all corresponding shear stress values (torque) against rate of shear values (rotational speed) as shown. The equation of this line was then manipulated to obtain the values for plastic viscosity (slope angle) and yield stress (intercept x-axis) as illustrated.

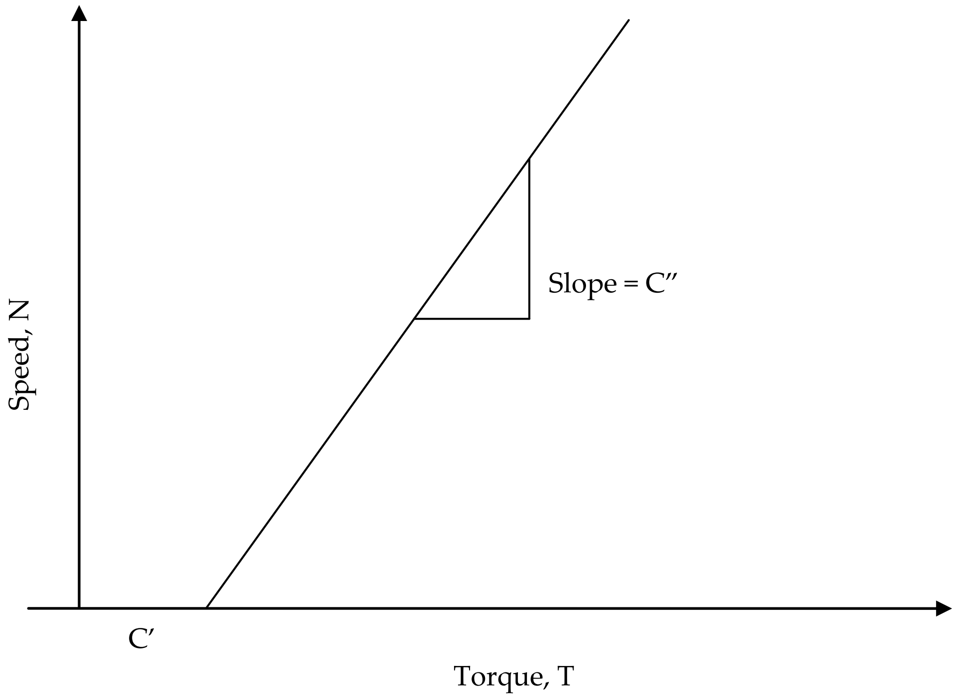


Figure 5.5: Relationship between torque, T and Speed, N for Bingham material (Tattersall, 1991)

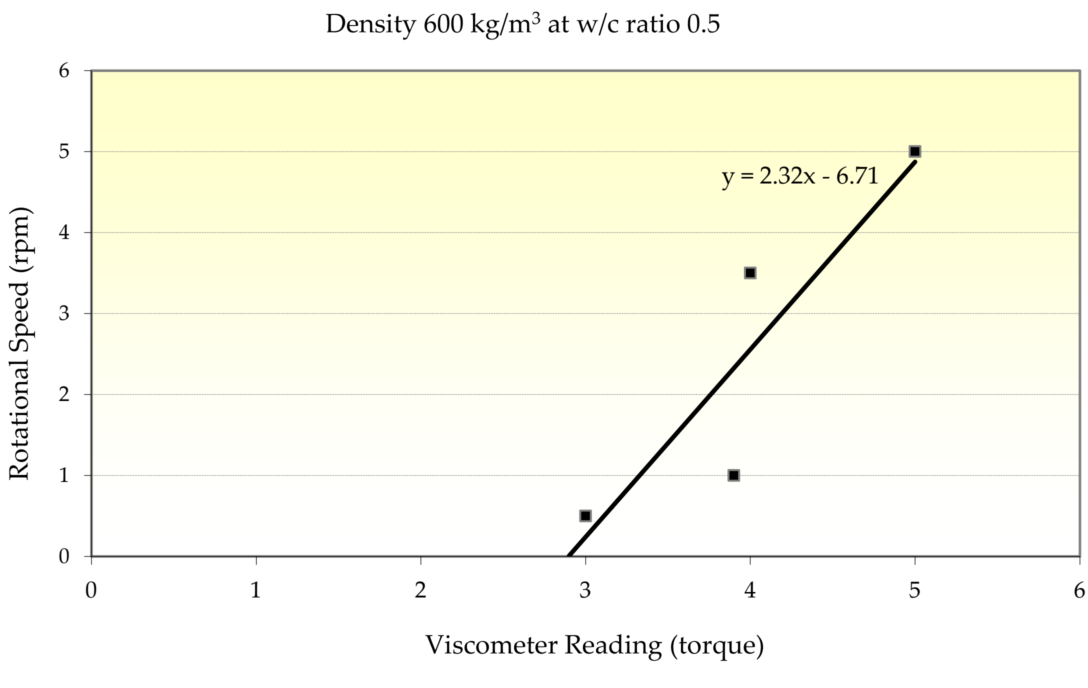


Figure 5.6: An example of rotational speed against viscometer reading

As shown in Figure 5.5, the relationship between torque and speed:

$T = C' + C''N$ *Equation 5.1*

where

T = torque (Nm)

C'' = slope of the line, where the reciprocal is the plastic viscosity

C' = intercept value at x-axis = yield stress

Using this similar equation, the calculation of yield stress and plastic viscosity can be obtained from this relationship:

$y = mx + c$ *Equation 5.2*

In this example (Figure 5.6), the equation of the line is $y = 2.32x-6.71$

where

m = slope

Plastic viscosity = 1/ tan (angle)

Plastic viscosity = 1 / 2.32

Plastic viscosity = 0.43 Ns/m^2

Yield stress is the point where it intercepts x-axis. Using the same equation; when $y=0$;

$x = 6.71 / 2.32$

$x = 2.89$

Yield Stress = 2.89 N/m^2

From this example, the value of plastic viscosity was 0.43 Ns/m^2 and yield stress 2.89 N/m^2.

5.3 RESULTS

The purpose of these experiments was to study the rheological behaviour of foamed concrete mixes by measuring the yield stress and plastic viscosity. When the shear stress was increased, the shear rate increased to a certain value, and then decreased to the starting point. The up and down curves did not coincide because foamed concrete is a thixotropic fluid. This is the hysteresis loop which is caused by the decrease in the fluid's viscosity with increasing time of shearing. In the current test, it was not possible to include the readings for up and down because of the sensitivity of the dial gauge.

The values obtained were apparent values, obtained empirically, and were used to suggest the pattern behaviour of foamed concrete specimens. In the current study, there were two sets of foamed concrete mixes. The first set consisted of foamed concrete using same constituent mixes with densities of 600 kg/m^3, 1000 kg/m^3 and 1400 kg/m^3 in various w/c ratios of 0.40, 0.50 and 0.60. In the second set, a wider variety of constituent materials were used at two selected densities (600 kg/m^3 and 1000 kg/m^3) and a greater range of w/c ratio; from 0.40 to 0.80.

5.3.1 Viscometer readings

Table 5.1 shows the rotational speed against the viscometer readings for all specified densities at varying w/c ratio in the first set of foamed concrete. Those at the lower range (0.5-5 rpm) were grouped as mode 1 and those at the higher range (10-50 rpm) were grouped as mode 2.

For density 600 kg/m^3, the graphs are shown in Figures 5.7, 5.8 and 5.9. As shown in Figure 5.7, there was a cluster of points at the lower speed. These points in the lower speed were then separated from the higher speed and these are presented as mode 1 (Figure 5.8) and mode 2 (Figure 5.9). A similar pattern was observed for foamed concrete density 1000 kg/m^3 and 1400 kg/m^3.

A possible explanation for this phenomenon was that, as foamed concrete moves through a section, the speed was slower at the pipe boundary (laminar flow) compared to the centre of the pipe, where the velocity speed was higher (turbulent flow). This is illustrated in

Figure 5.10. At the wall, the flow was slow moving, a condition represented as mode 1. After the flow has overcome the resistance at the boundary wall, the speed increased (mode 2).

Table 5.1 Rotational speed against viscometer reading

	Viscometer Readings (Torque) Nm								
Density (kg/m^3)	600			1000			1400		
Rotational Speed (rpm)	w/c ratio								
	0.4	0.5	0.6	0.4	0.5	0.6	0.4	0.5	0.6
0.5	6.9	3	1.3	13	8.5	1.3	40	35	15
1	7.2	3.9	1.5	14	10	1.4	50	40	22
3.5	8	4	2.3	25	14	5	55	45	35
5	9	5	2.5	27	15	7	70	60	37
10	9.4	5.25	3.1	30	18	9	74	64	38
20	9.5	5.5	3.4	32	19	10	75	65	40
50	12	7.5	5	35	22	11	91	79.5	48

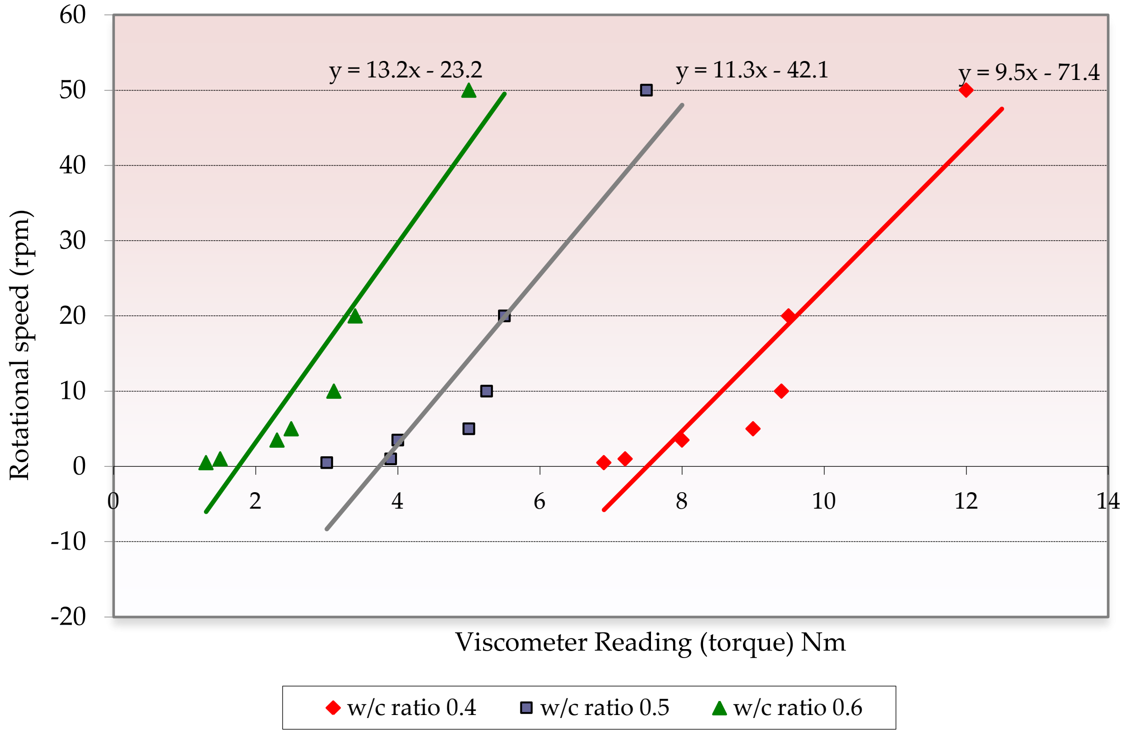


Figure 5.7: Rotational speed vs. viscometer reading for density 600 kg/m³ (combined)

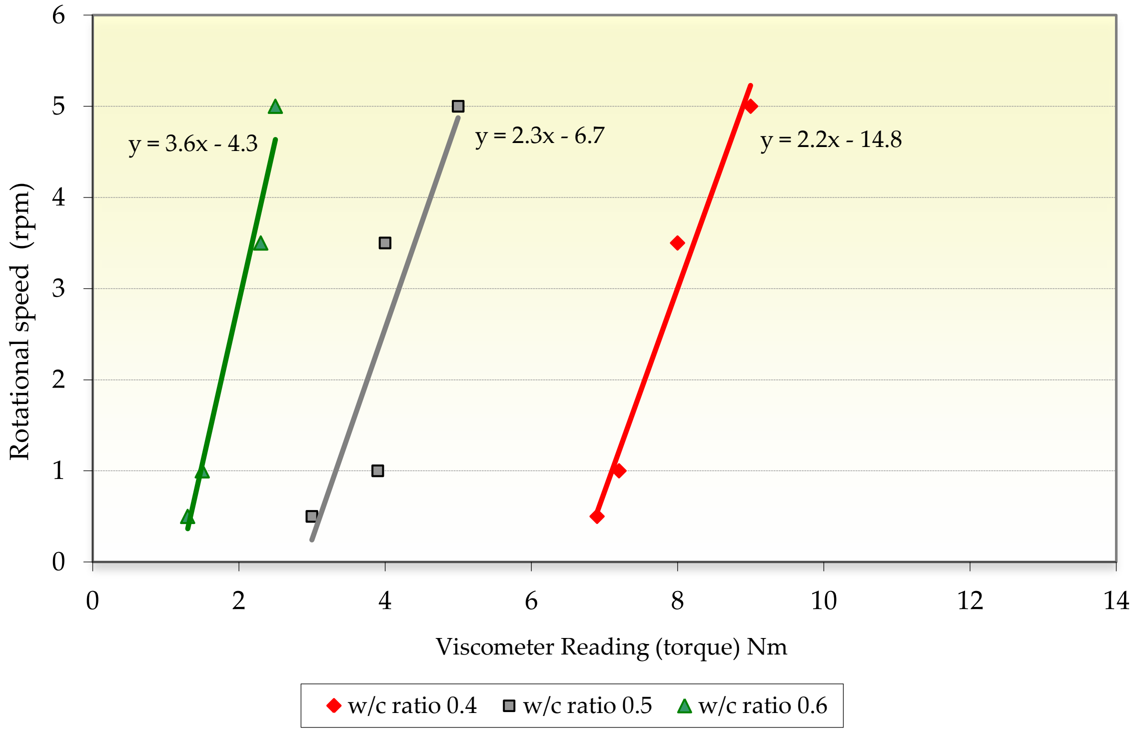


Figure 5.8: Rotational speed vs. viscometer reading for density 600 kg/m³ in mode 1

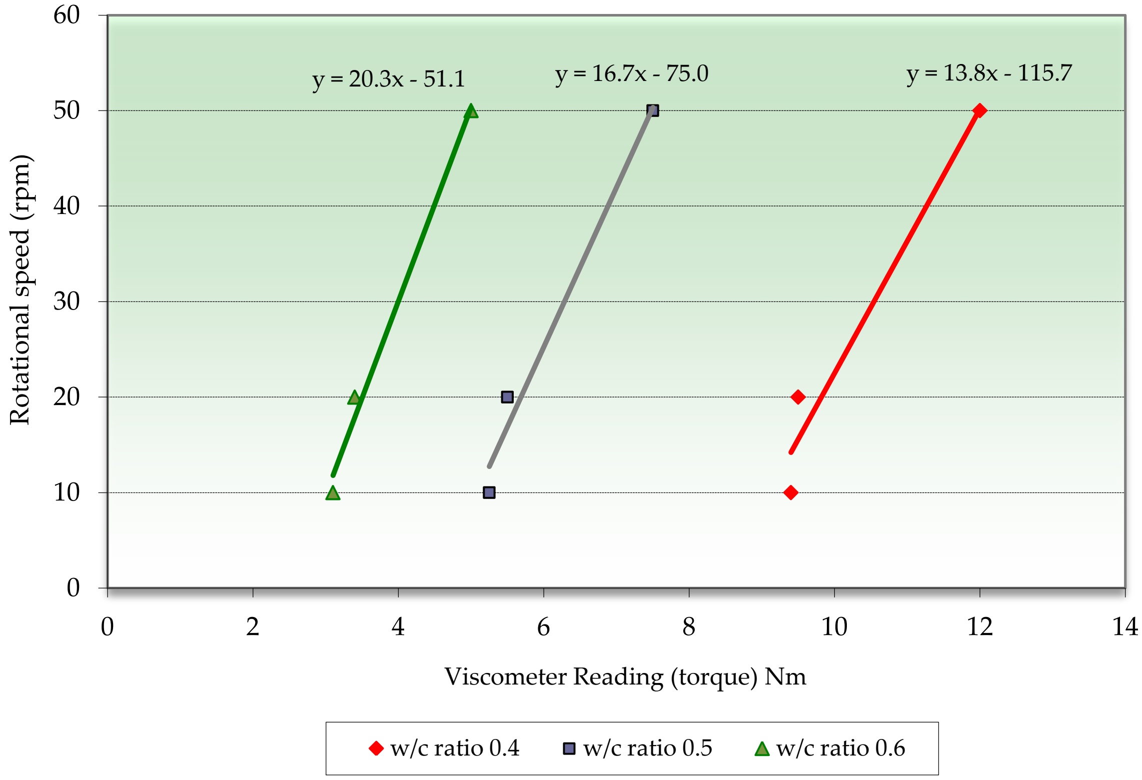


Figure 5.9: Rotational speed vs. viscometer reading for density 600 kg/m³ in mode 2

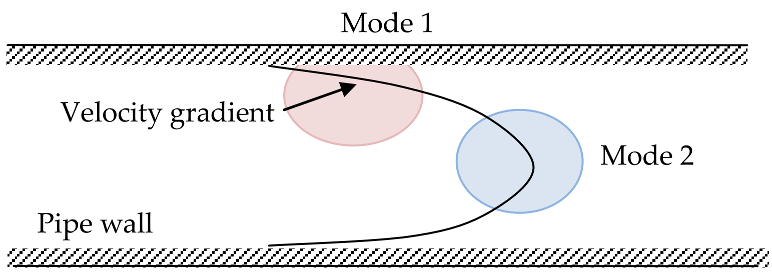


Figure 5.10: Mode 1 and Mode 2 boundary wall

5.3.2 Set 1

In the first set of experiments, the constituent materials used were the same for all six mixes. The variation was three different densities; 600 kg/m^3, 1000 kg/m^3 and 1400 kg/m^3 and three different w/c ratios; 0.40, 0.50 and 0.60.

1. Yield stress

Table 5.2 illustrates the values of yield stress and plastic viscosity obtained from calculations using the equations derived from the graphs of rotational speed and viscometer readings as described by the equation and Figure 5.6. The values were arranged according to densities at various w/c ratios. Despite the combined results being included in Table 5.2, the following graphs in Figures 5.11 and 5.12 show the results separately in mode 1 and mode 2. Mode 1 was the group of viscometer readings at lower rotational speed, whilst mode 2 was the group of readings at higher rotational speed from the Brookfield Viscometer. In both modes 1 and 2, there was an increase in yield stress as the density increases. However, the yield stress values decrease with increase in w/c ratio. This trend was similar in both modes 1 and 2. From these graphs, the lowest yield stress shown was found for density 600 kg/m^3 at w/c ratio 0.60, whilst the highest yield stress was density 1400 kg/m^3 at w/c ratio 0.40. These values implied that the strongest force; as indicated by highest yield stress, occurred in the highest density mix with lowest w/c ratio. In contrast, the lowest yield stress value was in density 600 kg/m^3 at highest w/c ratio, which implies the least force required to rotate the spindle. As mentioned, yield stress was the minimum stress required to initiate flow. In low density foamed concrete, the percentage of foam/air per volume was higher compared to high density foamed concrete which has higher percentage of solids, making it easier to initiate flow. In any one density, the low w/c ratio has higher yield stress value compared to higher w/c ratio. This was expected because having less water induced higher force to initiate flow.

2. Plastic viscosity

The two graphs in Figures 5.13 and 5.14 show the plastic viscosity for the different densities: 600 kg/m^3, 1000 kg/m^3 and 1400 kg/m^3 at three w/c ratios, 0.40, 0.50 and 0.60. The plastic viscosity in mode 2 was much lower compared to the values in mode 1. This was clearly shown even though the scale in Figure 5.14 is one-tenth of that used in Figure 5.13.

Plastic viscosity is the measure of internal resistance of fluid to flow. The initial stage where the rotational speed was low, the plastic viscosity was considerably high compared to high rotational speed. During the high rotational speed, the plastic viscosity was small, indicating there was less resistance. Figures 5.12 and 5.13 show that the plastic viscosity increased as the density increased. This implies that, at higher densities, the internal resistance for the fluid to flow is higher compared to that found at lower densities.

Plastic viscosity decreased with an increase in w/c ratio, even though the reduction was not significant in this set of readings. Since w/c ratio corresponded to the inter particles, increase in w/c ratio increased the inter particles. In these results, the highest plastic viscosity was found to be at the highest density, 1400 kg/m^3 and the lowest w/c ratio 0.40. In any one density, the mix with the highest w/c ratio showed the least plastic viscosity. This can be explained by the higher water content reducing the internal resistance; hence the mix becomes less viscous. A similar explanation is applicable to the lowest plastic viscosity, which was found at the lowest density, 600 kg/m^3 with the highest w/c ratio.

Table 5.2: Values of yield stress and plastic viscosity

Density (kg/m^3)	600			1000			1400		
w/c ratio	0.40	0.50	0.60	0.40	0.50	0.60	0.40	0.50	0.60
Yield stress (N/m^2)									
Mode 1	6.73	2.91	1.19	10.67	7.71	0.38	30.00	29.50	14.00
Mode 2	8.38	4.49	2.52	28.90	17.00	8.67	68.90	57.20	35.50
Combined	7.52	3.73	1.76	16.8	11.03	2.59	52.8	43.6	21.83
Plastic viscosity (Ns/m^2)									
Mode 1	0.45	0.43	0.28	3.49	1.49	1.32	6.25	5.38	5.16
Mode 2	0.07	0.06	0.05	0.12	0.1	0.05	0.47	0.42	0.25
Combined	0.11	0.09	0.08	0.66	0.33	0.29	1.19	1.07	0.85

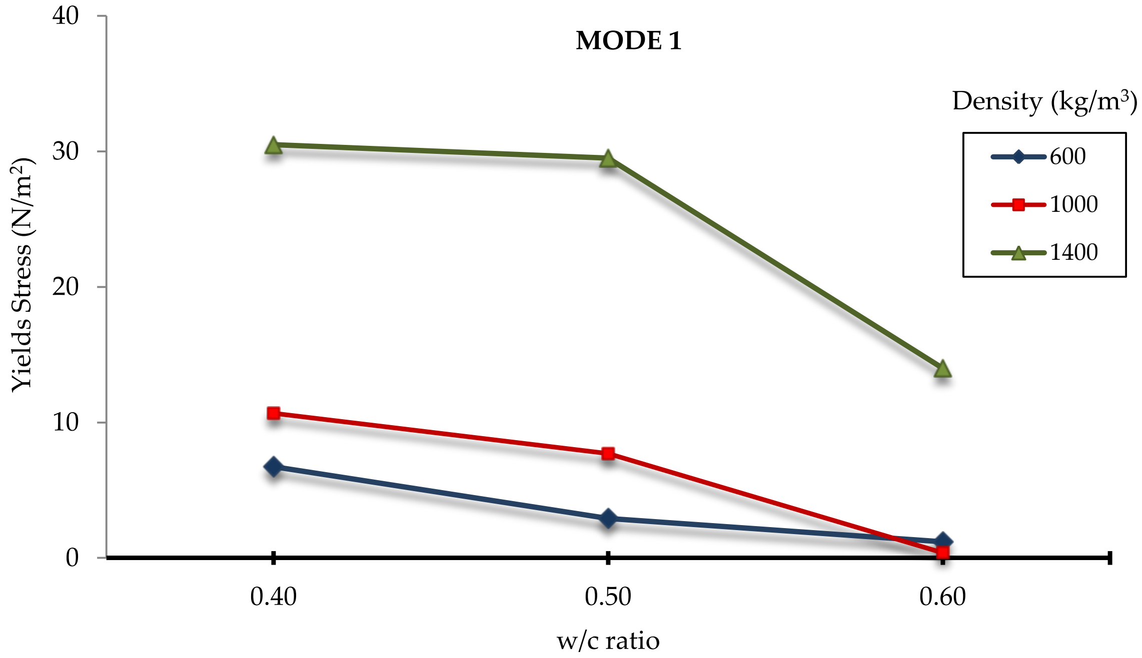


Figure 5.11: Yield stress values for different densities and w/c ratio in mode 1 (low rotational speed).

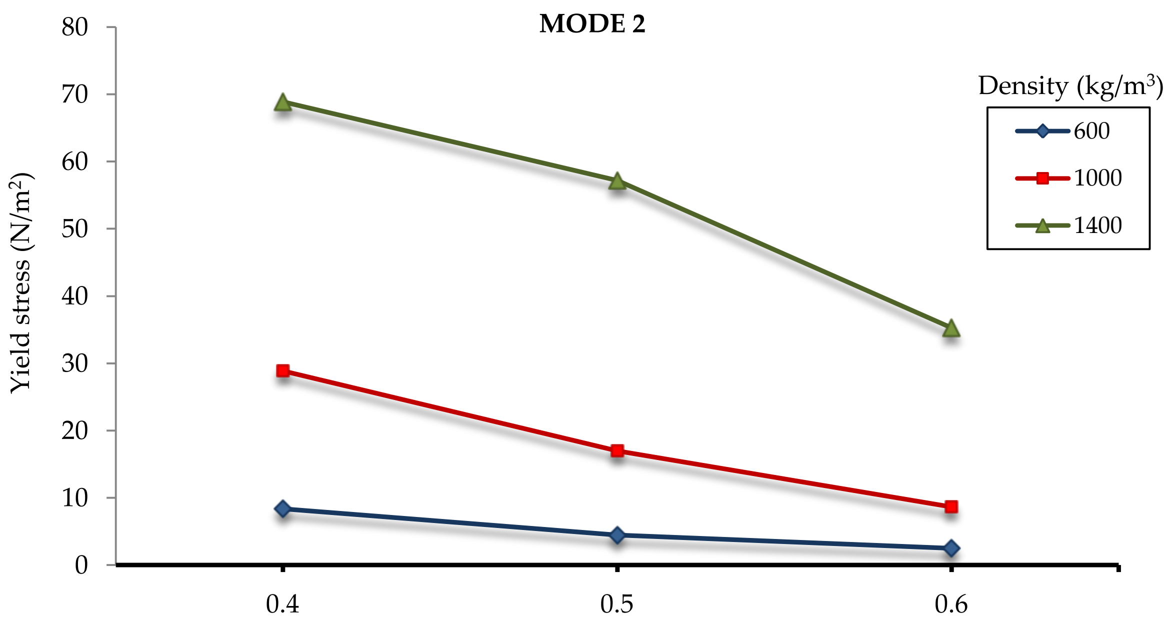


Figure 5.12: Yield stress for different densities and w/c ratio in mode 2 (high rotational speed).

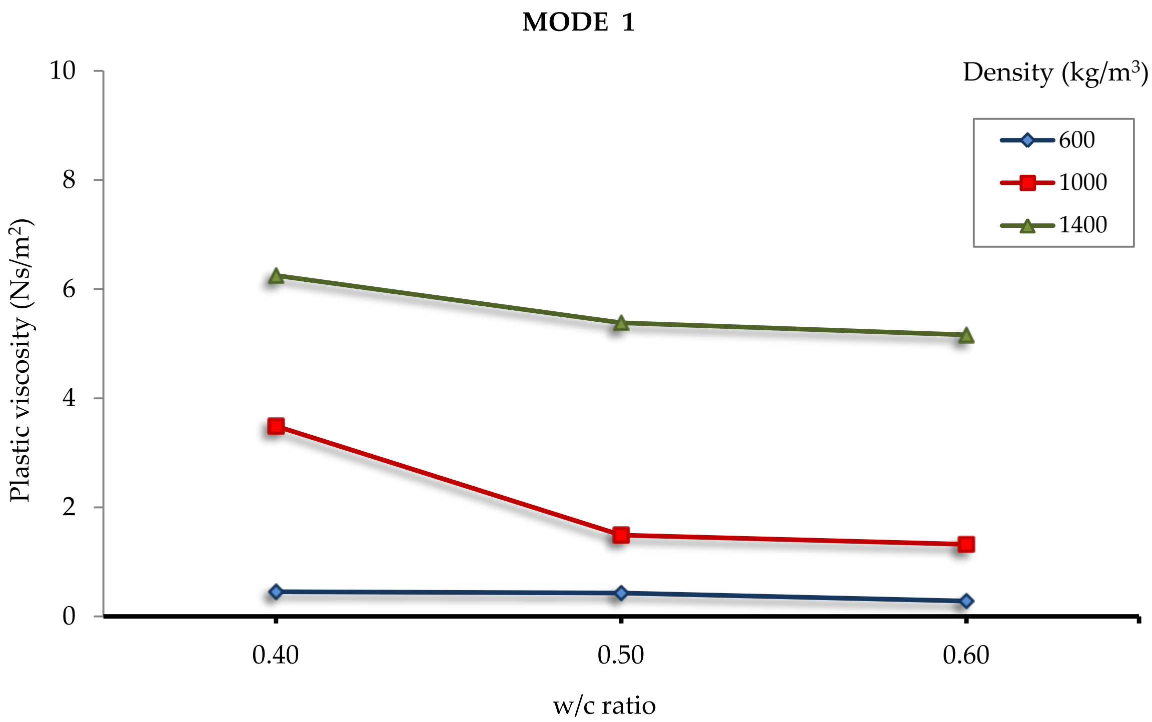


Figure 5.13: Plastic viscosity for different densities and w/c ratios in mode 1 (low rotational speed).

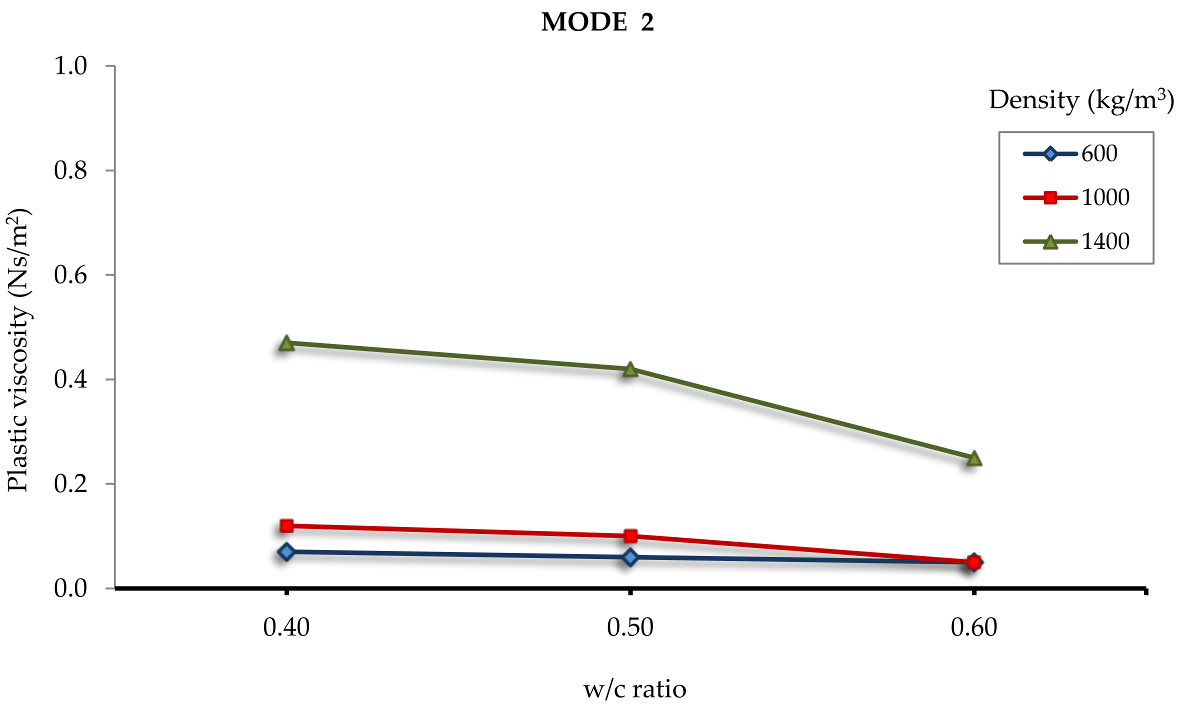


Figure 5.14: Plastic viscosity for different densities and w/c ratios in mode 2 (high rotational speed).

5.3.4 Set 2

In the second set of experiments, there were five mixes that used different constituent materials at various proportions which were mixed at density 600 kg/m^3 with w/c ratios from 0.40 to 0.80. For density 1000 kg/m^3, only three mixes were examined. The mix constituents and proportions for mix 1, mix 2 and mix 3 for density 600 kg/m^3 were identical to those of mix 1, mix 2 and mix 3 for density 1000 kg/m^3. Similar to the studies done in Set 1, the results in this set of experiments are also threefold: the study of rheological properties, instability and microstructure. The study of microstructure was illustrated in Chapter 6 and the results of instability were discussed in Chapter 7.

1. Yield stress

Table 5.3 presents the values of yield stress and plastic viscosity for all the mixes. Using these results, yield stress values of the mixes were plotted as shown in Figures 5.15 and 5.16. For density 600 kg/m^3, as shown in Figure 5.15, all five mixes show that yield stress decreased with increase in w/c ratio increase, even though the difference was minimal for mix 2. The highest yield stress value was for mix 3 at w/c ratio 0.40. This pattern was similar to that observed in mixes with density 1000 kg/m^3, as shown in Figure 5.16. However, at this density, for mix 3 at lower w/c ratios 0.40 and 0.50, the readings were not available as the mixes were too viscous such that the spindle did not rotate. Both graphs in Figure 5.15 and 5.16 show that, in all mixes, the highest w/c ratio produced the lowest yield stress. This implies that water content affects the behaviour of the foamed concrete mixes.

2. Plastic viscosity

Figures 5.17 and 5.18 show the plastic viscosity of the two different densities; 600 kg/m^3 and 1000 kg/m^3 respectively. The mix at w/c ratio 0.40 showed the highest plastic viscosity for all mixes which suggests that low w/c ratio creates the highest internal resistance to flow, hence high plastic viscosity values. Correspondingly, increase in w/c ratio increased the inter particles, as shown in both graphs, where plastic viscosity decreased with increase in w/c ratio.

Table 5.3: Yield stress and plastic viscosity

Density (kg/m³)		**600**	**1000**	**600**	**1000**
Mix	w/c ratio	Yield stress (N/m²)		Plastic viscosity (Ns/m²)	
MIX 1 : CEM I 42.5N + sand					
1	0.40	14.6	42.6	0.58	0.34
2	0.50	9.70	39.5	0.36	0.21
3	0.60	6.80	23.4	0.23	0.25
4	0.70	3.30	6.80	0.18	0.14
5	0.80	3.30	4.20	0.15	0.08
MIX 2: CEM I 42.5N (70%) + FA_f (30%) + sand					
1	0.40	8.40	31.3	0.58	0.33
2	0.50	7.30	19.30	0.23	0.24
3	0.60	4.60	11.90	0.35	0.13
4	0.70	5.20	4.30	0.15	0.12
5	0.80	3.80	4.50	0.23	0.08
MIX 3 : CEM I 42.5N (80%) + Metakaolin (20%) + sand					
1	0.40	50.5	N/A	3.03	N/A
2	0.50	15.30	N/A	0.60	N/A
3	0.60	10.0	19.40	0.45	0.28
4	0.70	7.10	14.70	0.46	0.18
5	0.80	4.70	3.40	0.29	0.09
MIX 4: CEM I 42.5N + sand (50%) + Coarse fly ash (50%)					
1	0.40	38.1	N/A	1.33	N/A
2	0.50	9.70	N/A	0.34	N/A
3	0.60	5.90	N/A	0.83	N/A
4	0.70	4.60	N/A	0.35	N/A
5	0.80	4.20	N/A	0.15	N/A
MIX 5: CEM I 42.5N + Coarse fly ash					
1	0.40	38.80	N/A	0.73	N/A
2	0.50	24.20	N/A	0.63	N/A
3	0.60	8.90	N/A	0.14	N/A
4	0.70	5.40	N/A	0.43	N/A
5	0.80	3.30	N/A	0.34	N/A

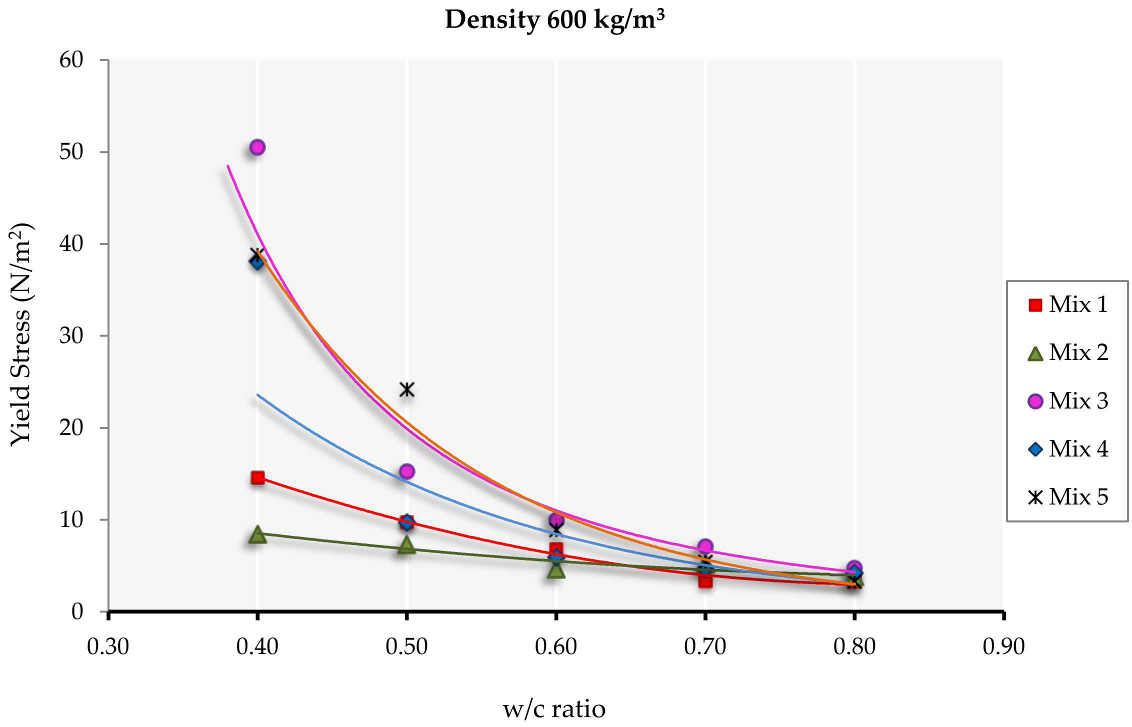


Figure 5.15: Yield stress values for mix 1, mix 2, mix 3, mix 4 and mix 5 for density 600 kg/m³

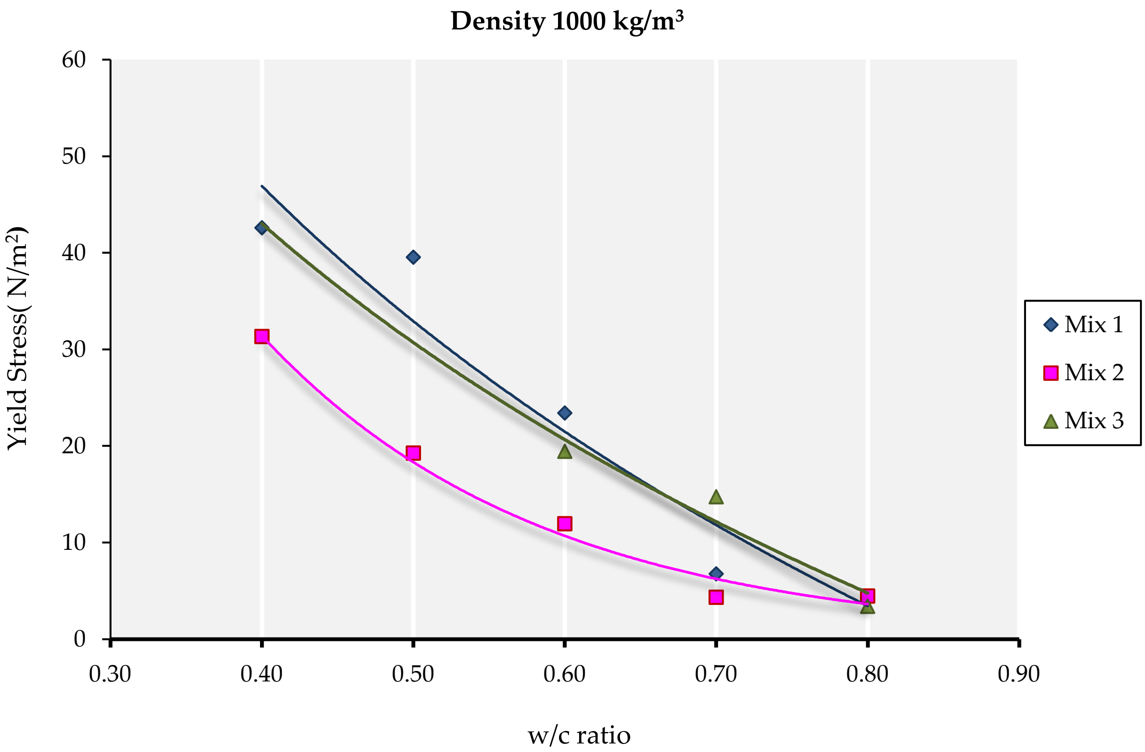


Figure 5.16: Yield stress values mix 1, mix 2 and mix 3 for density 1000 kg/m³

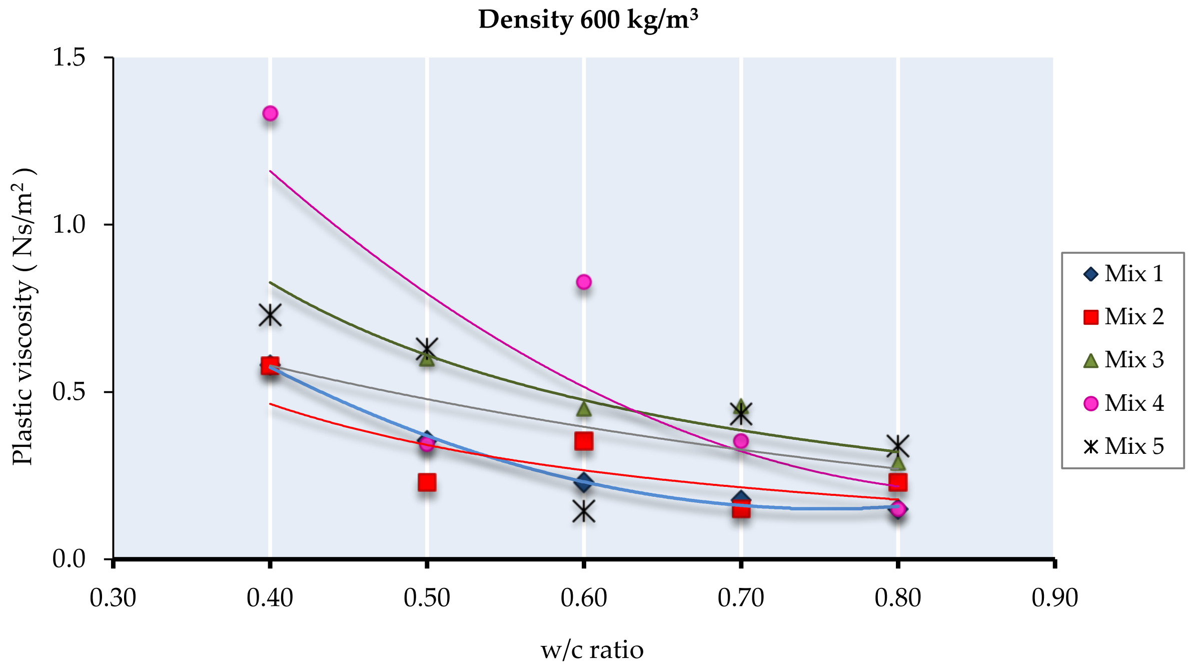


Figure 5.17: Plastic viscosity values for mix 1, mix 2, mix 3, mix 4 and mix 5 for density 600 kg/m³

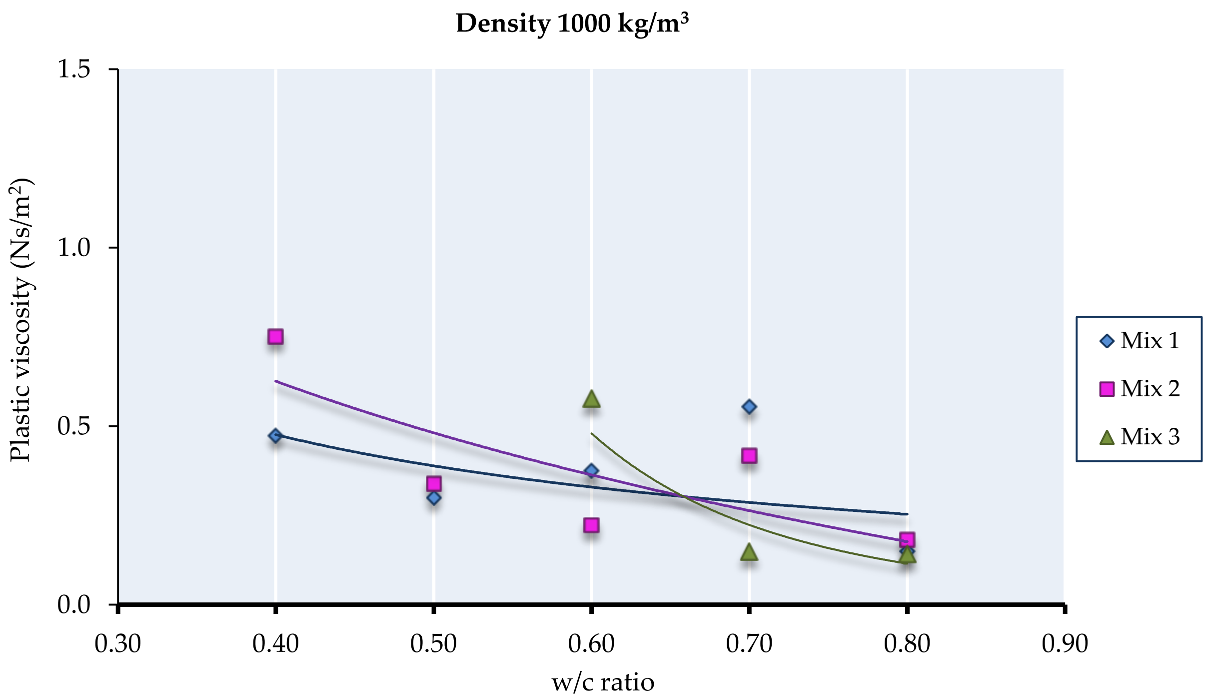


Figure 5.18: Plastic viscosity for density for mix 1, mix 2 and mix 3 for density 1000 kg/m³

When comparing the two densities; 600 kg/m^3 and 1000 kg/m^3, the yield stress values for density 1000 kg/m^3 were higher compared to yield stress for density 600 kg/m^3 (Figure 5.19). This is because the high percentage of solids in high density induced strong inter-particle forces. In contrast, the high percentage of foam content/bubbles in the low density mix hindered the flocculation of cement particles, resulting in decrease in yield stress.

For plastic viscosity, there was no general trend when comparing the two densities; 600 kg/m^3 and 1000 kg/m^3 (Figure 5.20). Both densities showed higher plastic viscosity at lower w/c ratio and decreased with higher w/c ratio. With the addition of metakaolin in mix 3, there was increased in water demand and the mixes showed higher resistance.

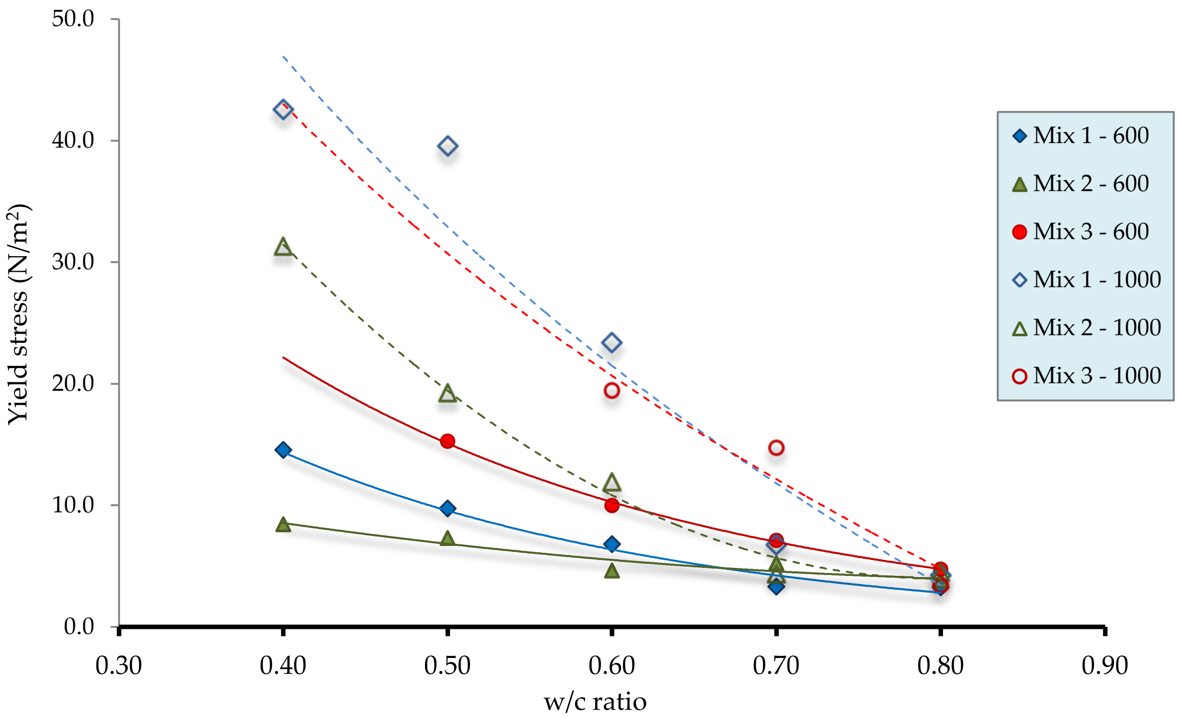


Figure 5.19: Yield stress values for density 600 kg/m³ and 1000 kg/m³

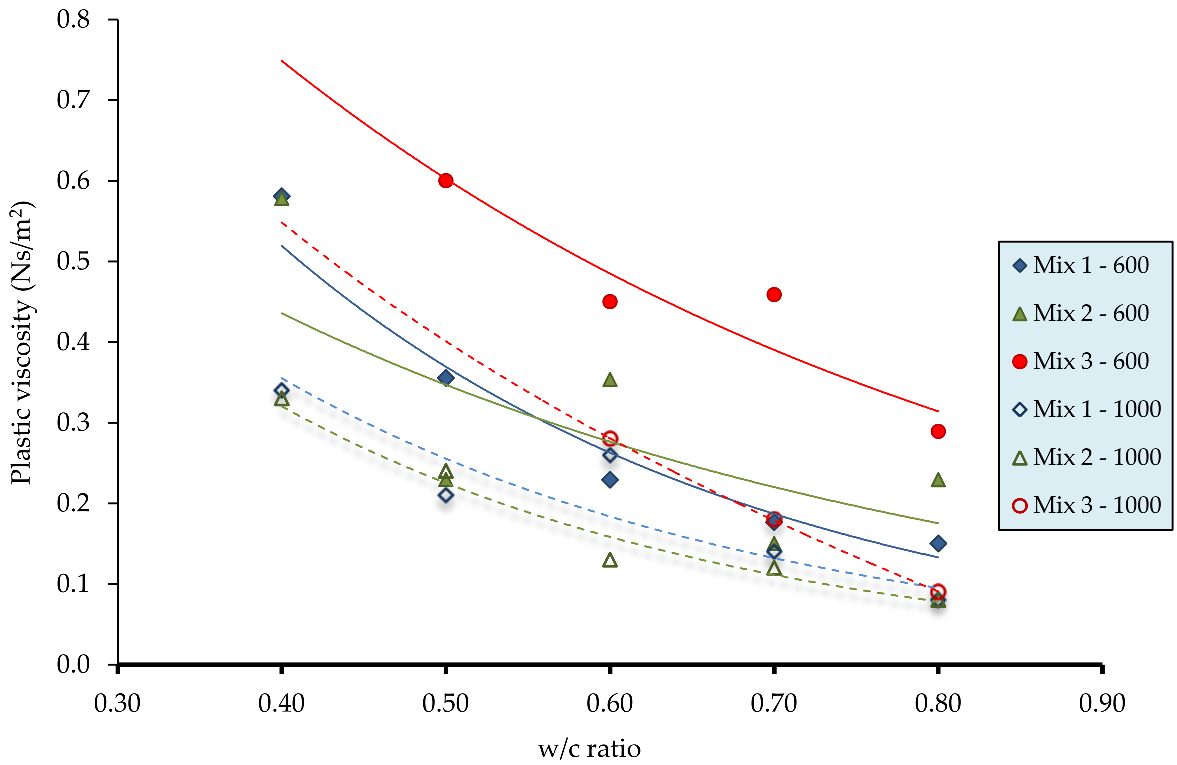


Figure 5.20: Plastic viscosity for density 600 kg/m³ and 1000 kg/m³

3. Fineness

In order to study the effect of fineness of cement and fillers, the values from Table 5.3 were arranged to show the different degrees of cement fineness. Figure 5.21 shows the yield stress values for mixes 1, 2 and 3 at density 600 kg/m^3. When metakaolin replaced CEM I 42.5N at 20 per cent, the yield stress increased markedly. This pattern was not repeated at lower w/c ratio for mix 2, where 30 per cent CEM I 42.5N was replaced with fine fly ash. Finer cements like metakaolin and fine fly ash required more water. At fixed w/c ratio, water was absorbed by the finer cements leaving less water for flow. This induced higher yield stress in the mixes. At high w/c ratio, the difference in yield stress values between the mixes were small. The variations indicate that although cement fineness has some effect, it was not a major factor affecting the yield stress.

In the same manner, when coarse fly ash replaced sand, the overall yield stress increased, albeit not significant. Figure 5.22 shows the yield stress values for mixes 1, 4 and 5 at density 600 kg/m^3. This graph shows the different filler combinations: mix 4 and mix 5 show slightly higher yield stress values compared to mix 1. Mix 4 has 50 per cent sand replaced with coarse fly ash and mix 5 has 100 per cent coarse fly ash. Coarse fly ash is finer than sand. These results suggest that finer fillers produced a higher yield stress although this may possibly be a secondary effect.

The plastic viscosity values for mixes of differing cement fineness are illustrated in Figure 5.23. Mix 3, where 20 per cent sand replaced with metakaolin shows the overall highest plastic viscosity. All the mixes show high plastic viscosity at lower w/c ratio. At high w/c ratios, the increase in plastic viscosity was not obvious, indicating that with sufficient water, the cement fineness may be less significant.

Figure 5.24 shows plastic viscosity values for mixes with differing filler fineness. There is no significant trend on the effect of filler fineness on plastic viscosity, although mix 5, having the highest fineness, shows the highest plastic viscosity. The filler fineness and the shape of filler particles possibly have some effect on the plastic viscosity but it is not a straight forward comparison.

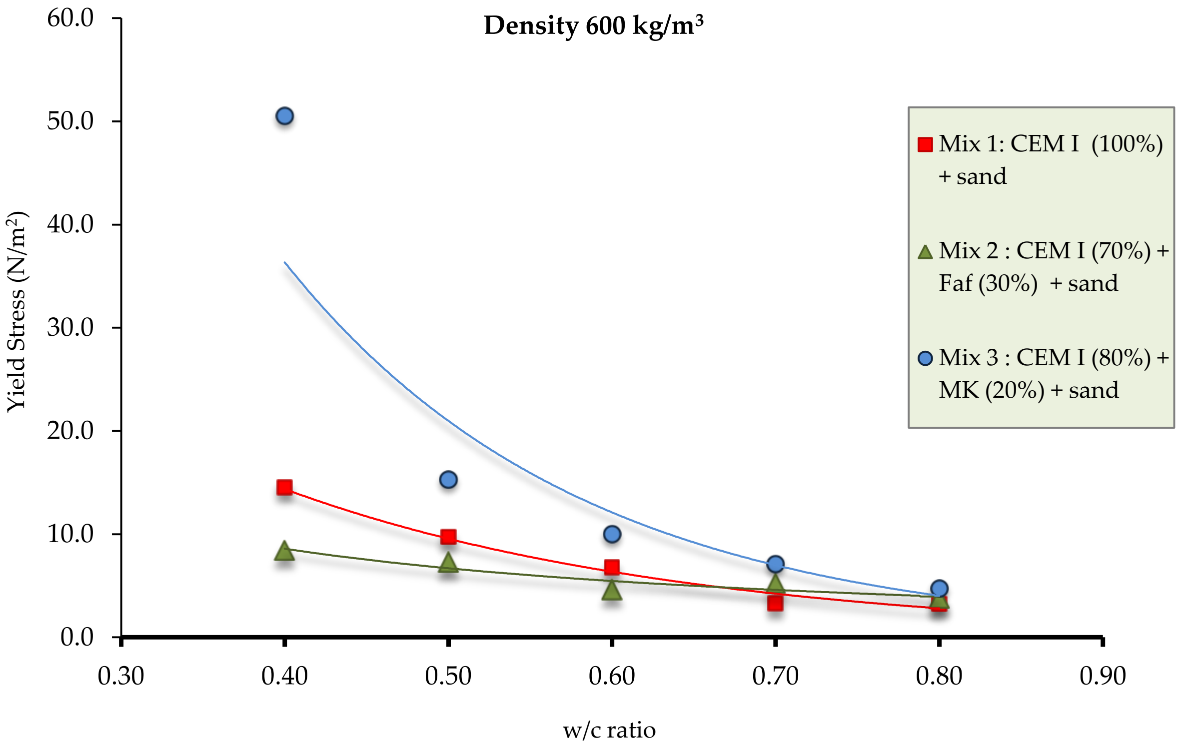


Figure 5.21: Effect of cement fineness on yield stress for density 600 kg/m³

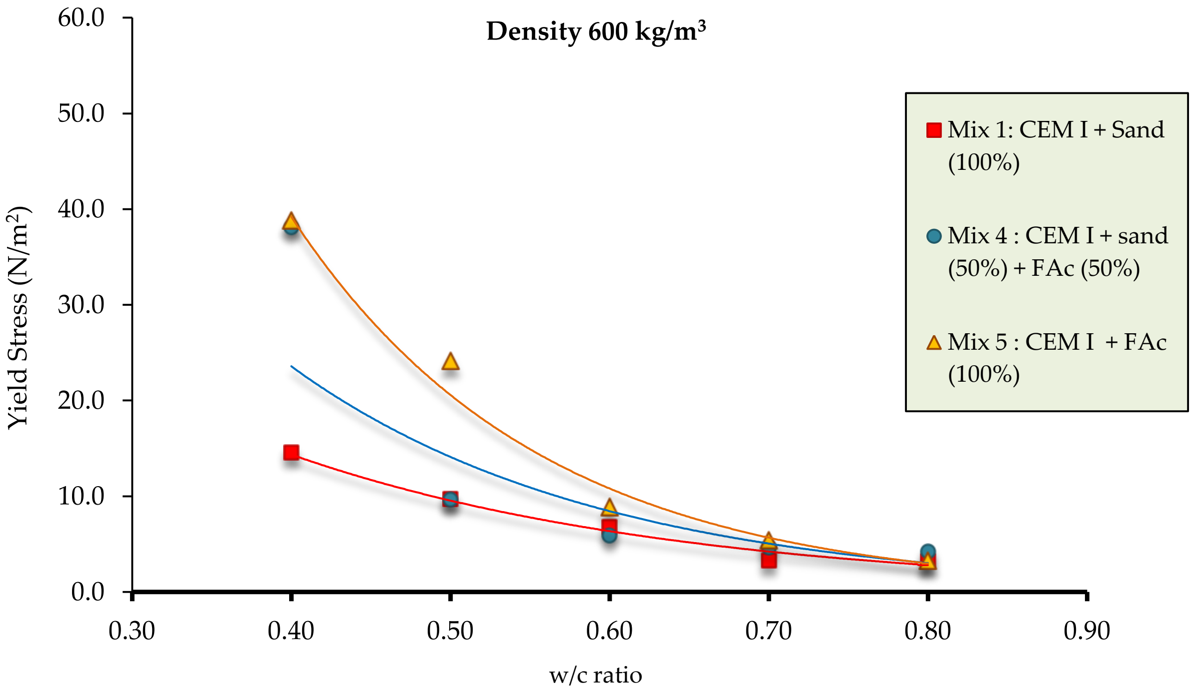


Figure 5.22: Effect of filler fineness on yield stress for density 600 kg/m³

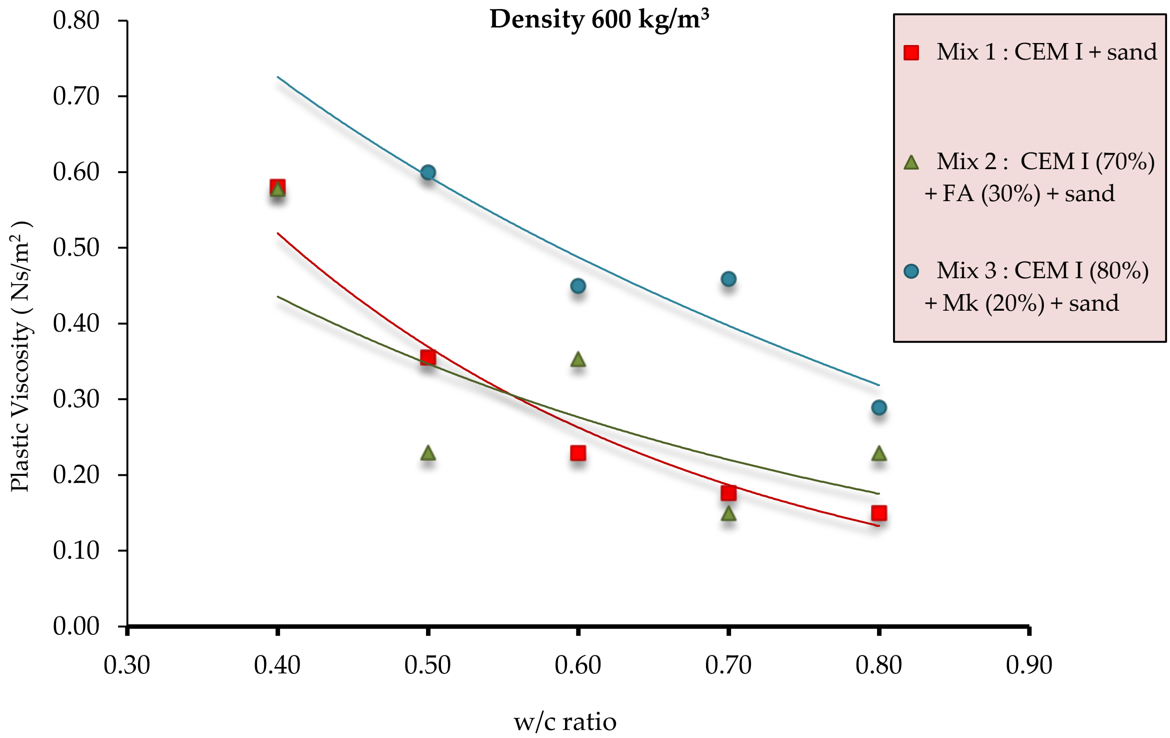


Figure 5.23: Effect of cement fineness on plastic viscosity for mixes 1, 2 and 3 at density 600 kg/m³

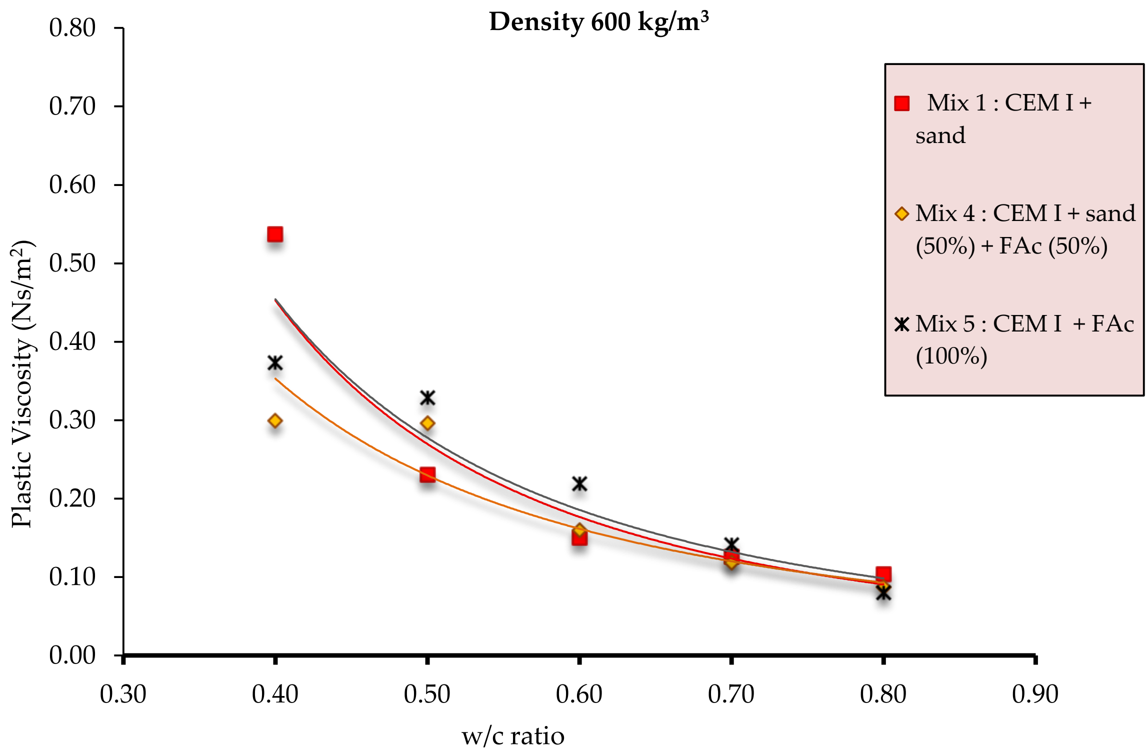


Figure 5.24: Effect of filler fineness on plastic viscosity for mixes 1, 4 and 5 at density 600 kg/m³

5.3.5 Consistence

Table 5.4 shows the Marsh cone time for all the mixes. The samples at w/c ratio 0.40 and 0.50 were not flowable for all mixes, with the exception of mix 2 at density 600 kg/m^3. Figure 5.25 shows the set of graphs which illustrate the Marsh cone time for density 600 kg/m^3 and Figure 5.26 shows the Marsh cone time for density 1000 kg/m^3. There was a sharp drop in the time taken from mixes at w/c ratio 0.60 to mixes at 0.70 in both densities. This phenomenon occurred because in this range there is free water available which facilitated flowability.

The flow time for mixes in density 600 kg/m^3 were longer compared to mixes in density 1000 kg/m^3, where available. This shows that density had an effect on consistence, where higher self-weight induced shorter flow time.

The flow time reduced noticeably when coarse fly ash, FA_c replaced sand. In Figure 5.25, the flow time reduced with 50 per cent fly ash replacement in mix 4 and further reduction when 100 per cent sand was replaced with FA_c in mix 5. The fineness of FA_c contributed to the increase in flowability because the spherical shape of FA_c induced ball bearing effect. As shown in Figure 5.26, the finer cements foamed concrete (mix 2 and mix 3) increased flow time at lower w/c ratios because the finer cements required more water for flowability. Metakaolin, which has higher fineness, replaced 20 per cent cement in mix 3. Due to this fineness, mix 3 required more water; thus the time taken was much longer at lower density. This is compared to mix 2 which incorporated fine fly ash, FA_f as 30 per cent cement replacement.

Two lines were marked at 1 minute and 3 minutes flow time (Figures 5.25 and 5.26). The range within these 2 lines was taken as 'ideal' flowability for application. This is assuming that the mixes taking more than 3 minutes to flow out were too slow, whilst mixes taking less than 1 minute suggest that the mix was too wet. These were empirical values and values within this range were assumed as flowable. In this study, the w/c ratios that fall within this 'acceptable' range were between w/c ratios 0.60 to 0.70. In mix 3, where metakaolin replaced CEM I 42.5N at 20%, flowability was only possible at higher w/c ratios. This was due to the high fineness of metakaolin which required more water to achieve flowability. Figure 5.27 shows the flowable mixes within the acceptable range (1 to 3 minutes in Marsh cone flow time). The mixes were mostly at w/c ratio 0.65 and corresponding yield stress values for these mixes between 6.0 to 8.5 N/m^2.

For higher density 1000 kg/m^3, only mixes 1, 2 and 3 were available for comparison. At lower w/c ratios 0.40 and 0.50, all three mixes were not flowable. The only point that fitted in the range of between 1 to 3 minutes was mix 3 at w/c ratio 0.7. This is in accord with hypothesis for density 600 kg/m^3, where w/c ratios between 0.60 to 0.70 present a good range for flowability.

Table 5.4: Marsh cone time

Density (kg/m^3)		600	1000
Mix	w/c ratio	Marsh cone (minute)	
MIX 1 : CEM I 42.5N + sand			
1	0.40	Not flowing	Not flowing
2	0.50	Not flowing	Not flowing
3	0.60	3:03	0:20
4	0.70	0:21	0:12
5	0.80	0:06	0:07
Mix 2 : CEM I 42.5N (70%) + FA_f (30%) + sand			
1	0.40	Not flowing	Not flowing
2	0.50	1:16	Not flowing
3	0.60	0:12	0:48
4	0.70	0:06	0:13
5	0.80	0:05	0:07
MIX 3 : CEM I 42.5N (80%) + Metakaolin (20%) + sand			
1	0.40	Not flowing	Very sticky
2	0.50	Not flowing	Very sticky
3	0.60	Not flowing	3:10
4	0.70	2:19	1:13
5	0.80	0:21	0:11
MIX 4: CEM I 42.5N + sand (50%) + FA_c (50%)			
1	0.40	Not flowing	N/A
2	0.50	Not flowing	N/A
3	0.60	2:10	N/A
4	0.70	0:14	N/A
5	0.80	0:11	N/A
MIX 5: CEM I 42.5N + FA_c			
1	0.40	Not flowing	N/A
2	0.50	Not flowing	N/A
3	0.60	1:35	N/A
4	0.70	0:13	N/A
5	0.80	0:05	N/A

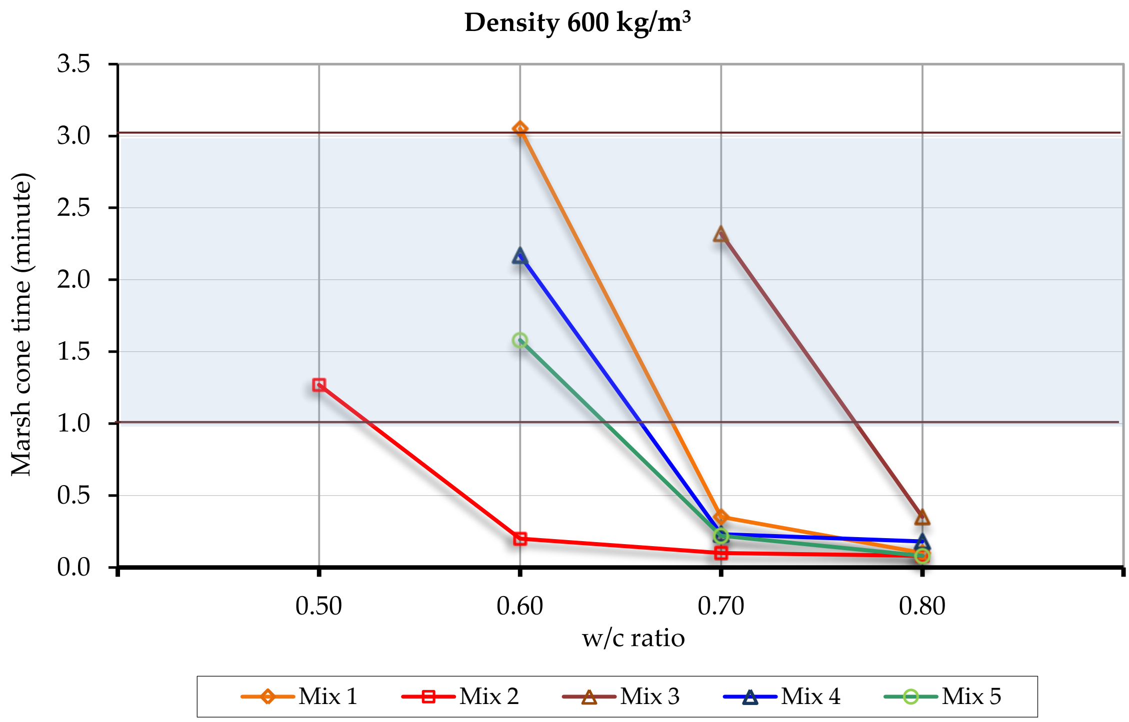


Figure 5.25: Marsh cone time for density 600 kg/m³

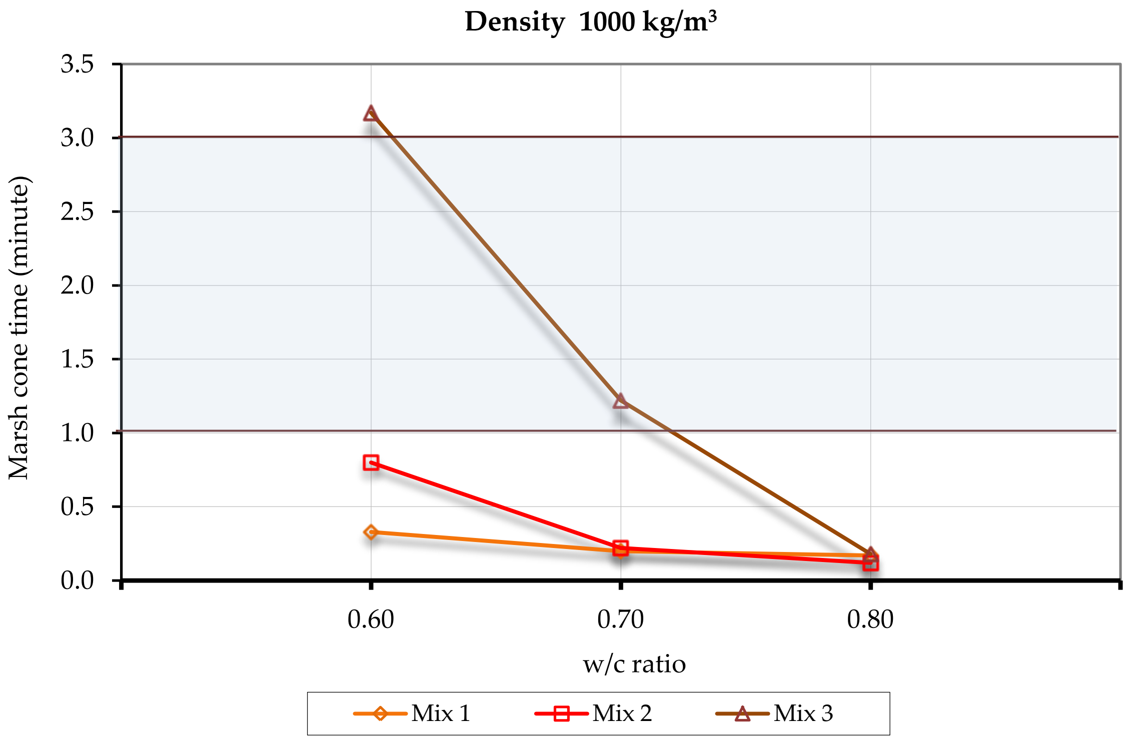


Figure 5.26: Marsh cone time for density 1000 kg/m³

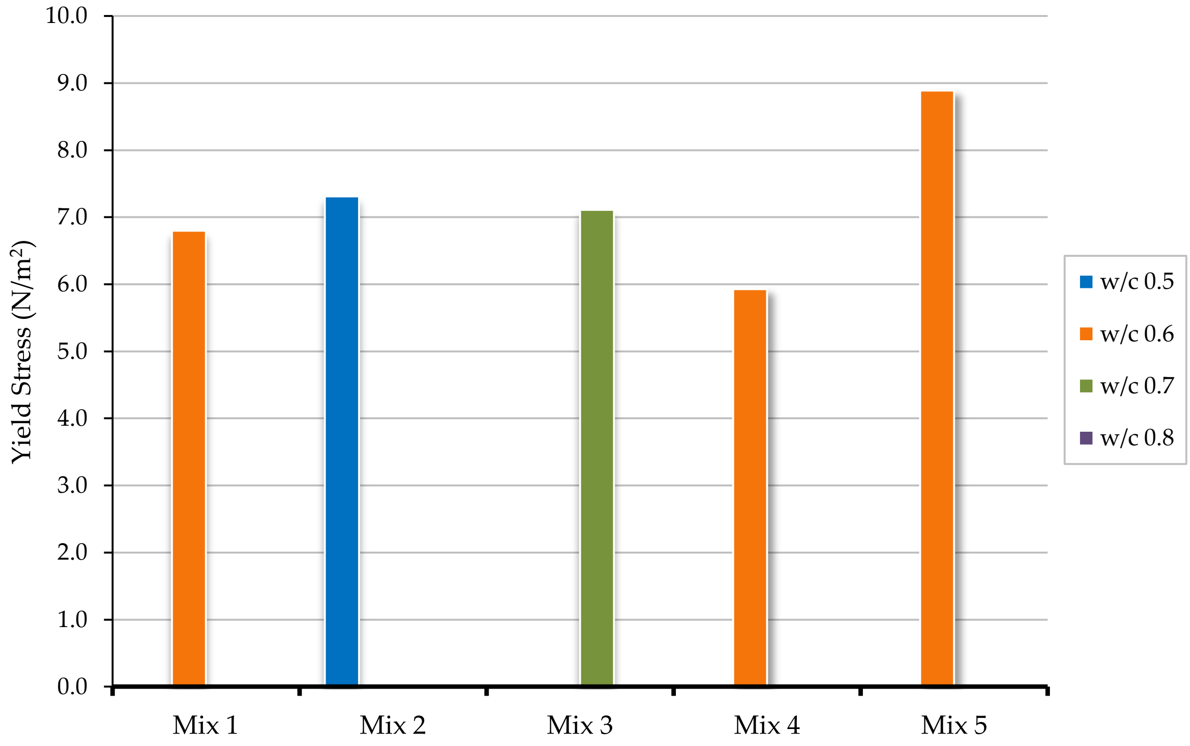


Figure 5.27: Yield stress values for flowable foamed concrete at density 600 kg/m^3

5.4 SUMMARY OF RESULTS

This chapter reports observations on the rheological properties of foamed concrete that were found by establishing the values of yield stress, plastic viscosity and flow time of different mixes. These values, obtained empirically, were used to study the effect of constituent materials and their proportions. Density was the dominating factor in yield stress, plastic viscosity and consistence of foamed concrete. The second controlling factor was w/c ratio. Fineness and proportion of constituent materials affected the rheology of foamed concrete although the effect was not as significant.

Significant outcomes arose from this phase of the study.

1. Yield stress increased with increase in density, a pattern observed in all mixes of varying constituent materials.
2. Yield stress, by contrast, decreased with increase in w/c ratio.
3. Plastic viscosity increased when density increased and decreased with increase in w/c ratio. However, this was not significant within a small range of variation; w/c 0.40 to w/c 0.60. The decrease was significant in a larger variation; w/c 0.40 to w/c 0.80.
4. Yield stress values increased when the cementitious fineness was increased. This is markedly evident at the higher w/c ratios. However plastic viscosity did not increase for all mixes when the cement fineness was increased. Increase in filler fineness increased the yield stress and plastic viscosity in general, although there were a few mixes which did not observe this trend. Fineness in cements and fillers did not have significant effect on rheological properties.
5. Density and w/c ratio affected the consistence of foamed concrete. Higher density reduced the flow time. For a given density, a higher w/c ratio reduced the flow time.
6. Coarse fly ash increased flowability when replaced sand as filler.
7. Mixes within flowable time corresponded to mixes at w/c ratio in the range of 0.60 to 0.70. In this range, the yield stress values were between 6.0 N/m^2 to 8.5 N/m^2.

CHAPTER 6: BUBBLE MICROSTRUCTURE / AIR VOID SYSTEM

6.1 INTRODUCTION

Microstructure refers to the microscopic description of the individual constituents of a material. The type, amount, size, shape and distribution phases present in the material constitute its microstructure in a solid. Pore structure is a very important microstructural characteristic in a porous solid because it influences the physical and mechanical behaviours of porous material (Kalliopi, 2006). The physical structure of the products of hydration of cement and their relative volumetric proportions affect the durability of hardened cement paste to a greater extent than the chemical composition (Mehta, 2000).

Foamed concretes consist of air voids of approximately 0.1 to 1 mm in size, uniformly distributed in a matrix of fillers and cements (Wee et al., 2006). Several researchers are in accord on the paramount importance of adequate void system for the production of foamed concrete (Kearsley 1999; Nambiar and Ramamurthy, 2000a; Aldridge, 2005; Hamidah et al., 2005; and Nambiar and Ramamurthy, 2007a). Given that the air voids are separated and coated with cement paste during mixing and placing, the skin of the air voids must be tough and persistent in order to withstand these activities (Wee et al., 2006). On a microscopic scale, the most important properties of foamed concrete are the air void shape, spacing factor and size distribution (Nambiar and Ramamurthy, 2007). These properties are important, as they are responsible for a tenfold change in compressive strength, rather than common w/c ratio and aggregate-cement ratio found in conventional concretes (Beningfield, 2005).

In higher density foamed concretes, the spherical air voids are more distinct with even distribution throughout the matrix and are more uniform in size compared to the lower compressive strength foamed concretes (Nambiar and Ramamurthy, 2007). By contrast, in foamed concrete at lower densities, where the foam volume is high, the bubbles merge and produce larger voids. These larger voids have uneven openings and irregular air void perimeters (Kearsley and Visagie, 1999).

The factors that govern this phenomenon in the lower density concretes are the subject of this investigation because the stability of the foams is of paramount importance in foamed concrete (Dransfield, 2000; Aldridge, 2000; Jones and McCarthy, 2006). Given that there are many factors which influence the stability of the foam, this study also investigated other parameters which affect the size, shapes and distribution of the air-voids. For the purpose of this thesis, the terms 'voids' and 'bubbles' have been used interchangeably.

6.2 MATERIALS, EXPERIMENTAL PROGRAMMES AND METHODOLOGY

6.2.1 Introduction

The overall aim of this study was to investigate the microstructure of foamed concrete in relation to varying densities, water/cement ratios (w/c ratio) and different combinations of material constituents. The microstructure of all concrete is highly complex and heterogeneous, which makes it difficult to characterise the pore structure (Kalliopi, 2006 and Mehta, 2006). To date, there has been no standard method for the study of the microstructure of foamed concrete. Several indirect methods have been used by other researchers including Kalliopi (2006) based on the ASTM C457–Standard Test Method for the Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete. Kalliopi (2006) used section analysis, which is a method used in stereology. This method requires rigorous surface preparation which involves the specimens being ground and polished. High air content concrete such as foamed concrete contains air voids which tend to coalesce and the fragile thin walls between the voids can be damaged easily during grinding; this can impair the accuracy of the measurements.

Kearsley and Visagie (1999) and Nambiar and Kunhanandan (2007a) adopted a method using a high resolution camera and image analysis software. Taking cognisance of their work, the current study adopted a similar approach to investigate the microstructure of foamed concrete. The image analysis software employed was 'ImageJ'.

6.2.2 Constituent Materials

1. Portland cement PC, CEM I 42.5N conforming to BS EN 197-1 was the main cement employed in the study. In Set 3 study, CEM I 52.5R was employed.

2. 'Fine' fly ash (FA_f) with a 45 μm sieve retention of 7.5%, loss on ignition (LOI) of 5.0% and conforming to BS EN 450.5 was used to replace CEM I 42.5N at 30% by mass fraction.

3. Metakaolin used as replacement for cement to a level of 20% in the second study (Set 2).

4. Calcium sulphoaluminate (CSA) was employed in the Set 3 study. CSA is a quick setting and early strength cement, which is finer and lighter in colour compared to CEM I 42.5N.

5. The main filler was natural sand, fine aggregate (conforming to BS EN 12620: 2002 with particles greater than 2.36 mm removed by sieving).

6. Coarse fly ash, FA_c with a 45μm sieve retention of 36.0% and conforming to BS 3892-2/ BS EN 450 and ASTM C 618-94a Class F was used as 50% and 100% replacement for sand.

7. The surfactants used in this study were synthetic and protein-based surfactants which were commercially available. For both surfactants, the dilution was 6% aqueous solution which produced foamed to a density range of 40 - 50 kg/m^3.

8. The mixing water used conformed to BS EN 1008 Mixing water for concrete. In this study, the w/c ratio was varied from 0.40 to 0.80.

9. Wetting agent at 1% and 2% of cement weight was incorporated.

6.2.3 Experimental Programme

There were two main sets of experiments: Set 1 and Set 2 (Figure 6.1). In Set 1, a set of consistent constituent materials were used - cement and filler types and two types of surfactants. The variations were in their densities, w/c ratios and with addition of wetting agents. The densities were 600 kg/m^3, 1000 kg/m^3 and 1400 kg/m^3 and the w/c ratios were 0.40, 0.50 and 0.60. For Set 2, besides the range in the densities and w/c ratios, the variations included the cement and filler types. Set 3 used different cement combinations. Contrary to Set 1 and Set 2, where the main cement was CEM I 42.5N, the main cement in Set 3 was CSA. In this set, the density was fixed at 300 kg/m^3 and the variations were in the cement combinations and varying w/c ratios. No fillers were included in this set, owing to the low density.

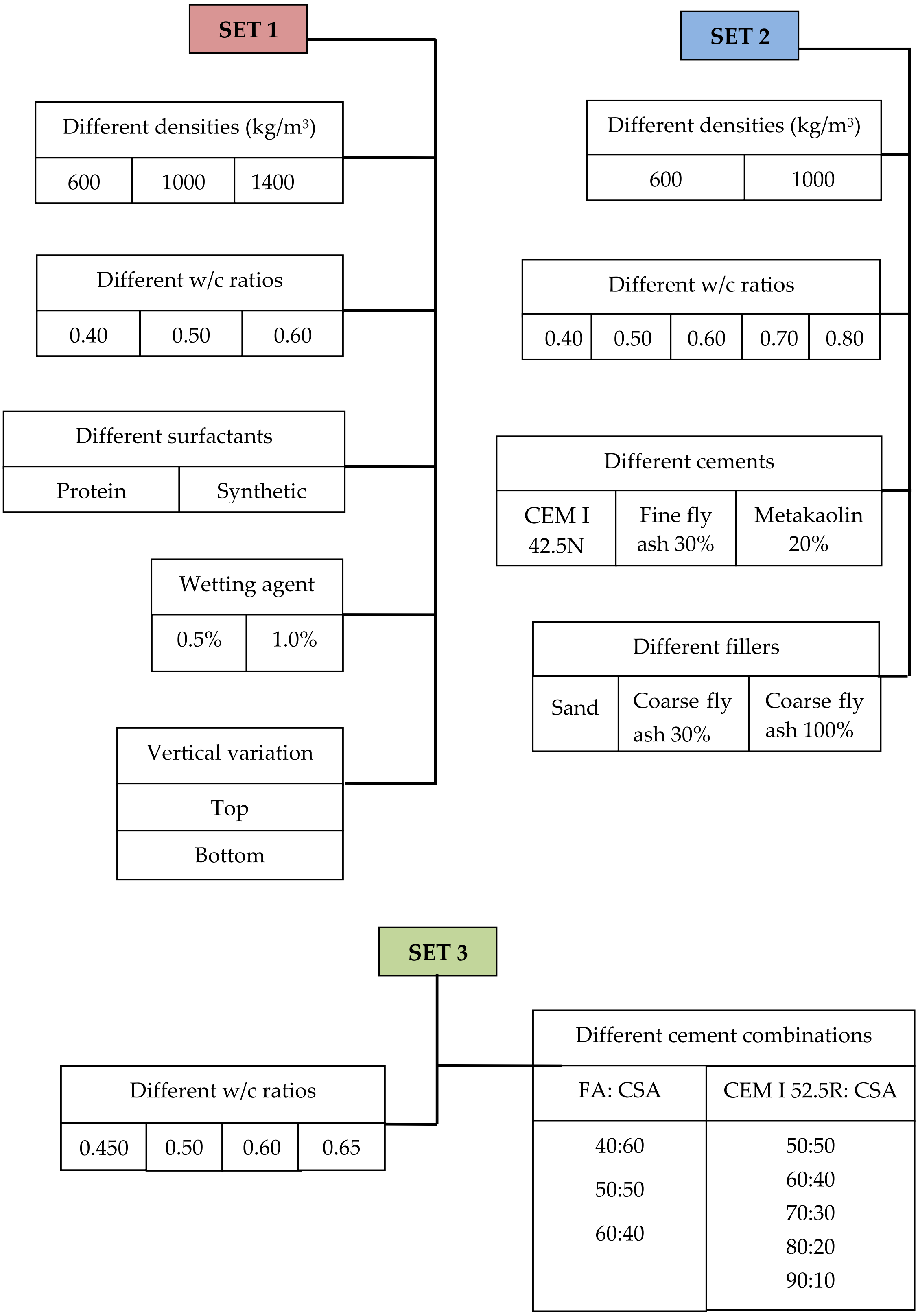


Figure 6.1: Experimental Programme

6.2.4 Methodology

Based on the experimental programme, there were three parts to the study. Each set had its own constants and variations of the constituent materials and their proportions. The study of microstructure of foamed concrete was based on data obtained mainly from image processing and image description, where appropriate.

6.2.4.1 Preparations of specimens

The foamed concrete was produced in the laboratory using a Hobart mixer. This mixer allows small mixes to be produced and offers better control in speed at the convenience of managing the mixing time. The base mix was first produced by mixing sand (or FA_c), cements and water until a uniform consistency was achieved. Then the preformed foam was added to the base mix and the mixing continued until all the foams were uniformly incorporated and distributed. Next, the plastic density was measured in accordance with BS EN 12350-611 by weighing a foamed concrete sample in a pre-weighed container of a known volume. A tolerance on plastic density was set at ± 50 kg/m^3 of the target value as being acceptable.

The specimens were then cast in cylinder moulds lined with domestic plastic 'cling' film to avoid the foamed concrete from adhering strongly to the mould surface. The cylinder heights varied from 300 mm to 500 mm. The heights were randomly selected to observe the distribution of bubbles throughout the differing heights and to study the amount of drop in level which is used as indicator for instability. These readings were used in the study of instability which is covered in Chapter 7.

After 24 hours, the foamed concrete was de-moulded and the specimens were sealed-cured by wrapping in 'cling' film to avoid direct exposure to wind and, hence, decrease evaporation (Figure 6.2). They were stored at 20^{0}C until testing.

6.2.4.2 Surface Preparations

The preparations of the specimens depended upon the densities. They were spilt longitudinally, which produced two long specimens (Figure 6.3). The specimens from lower densities of foamed concrete were cut off using a metal saw, whilst the higher densities were split by employing a splitting machine (Figure 6.4). From the longitudinal specimens, the length of the cylinder was 'divided' into four sections which enabled the study of microstructure in relation to their position the top and bottom section, as shown in Figure 6.3.

The specimens were of varying depths, but the most important aspect was that the surface was level. The specimens were cleaned with compressed air to remove loose deposits from the effects of splitting. The conventional surface preparation method of filling pores with a synthetic resin and smoothing by grinding was not suitable for foamed concrete. This process may disrupt accuracy by disturbing the thin walls and induces cracks during the grinding and polishing operations. Only foam concrete specimens with an excellent quality surface are subjected to image analysis measurement.

Figure 6.2: Foamed concrete specimen wrapped in 'cling' film

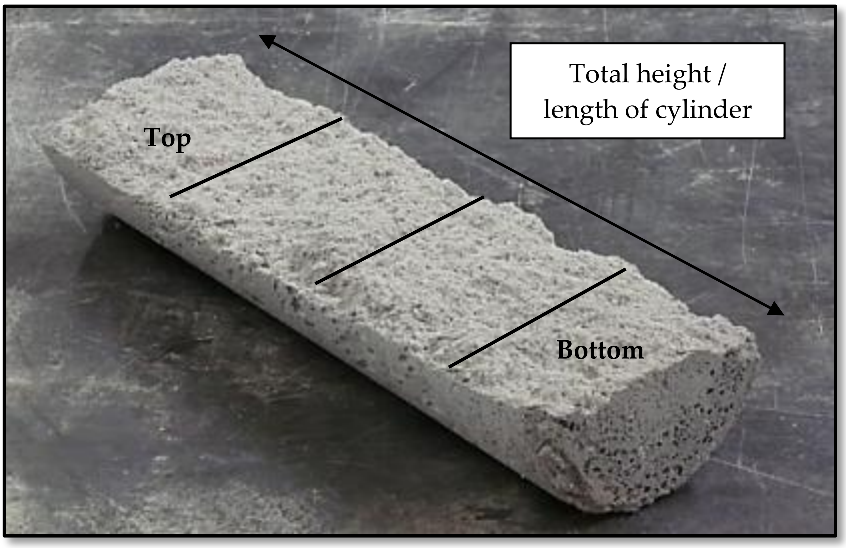


Figure 6.3: Cylinder specimen split in half longitudinally

Figure 6.4: Splitting machine

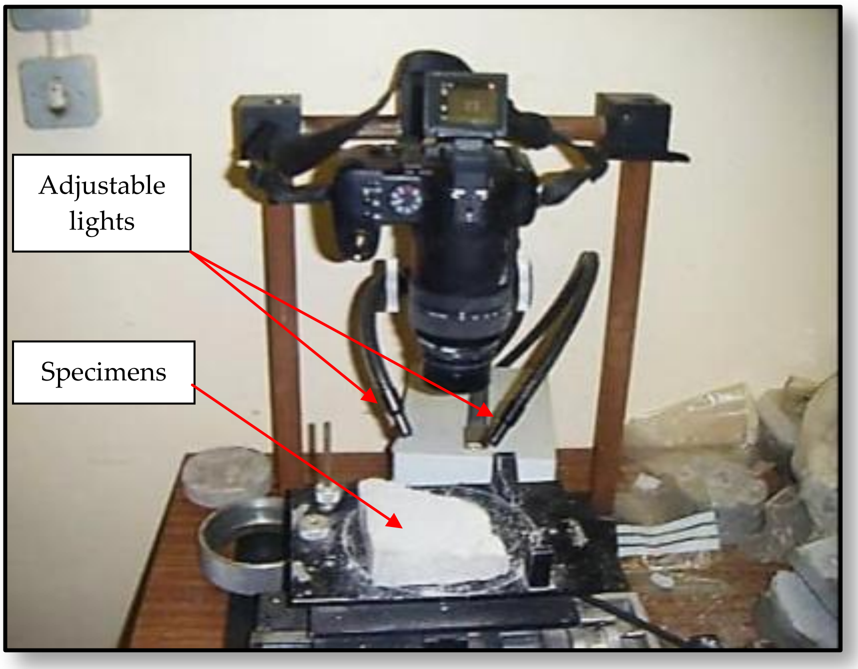


Figure 6.5: High magnification SLR camera mounted on tripod

6.2.4.3 Image Processing and Analysis

The objective was to obtain a clear, magnified image using a digital camera at high magnification. This was achieved using a single-lens reflex (SLR) camera with a number of kit lenses, which were able to magnify objects. The camera was securely mounted on adjustable short tripod, and the specimens were placed beneath the camera (Figure 6.5). Under adequate built-in lighting, every image was captured adjacent to a scale and the images were uploaded to a computer. This technique required some skill because shadows may interfere with the images captured. A total of 2 clear images were selected from each section of a specimen. Analysis was carried out using software 'ImageJ' which is a freeware and downloadable from the internet address: http://rsbweb.nih.gov/ij/download.html.

However, the analysis using imaging techniques is not straight forward. The common sources of errors included the wide range of specimens in the same group, the selection of area for analysis and identification of the microstructure.

6.2.4.4 Method Statement for Image Processing

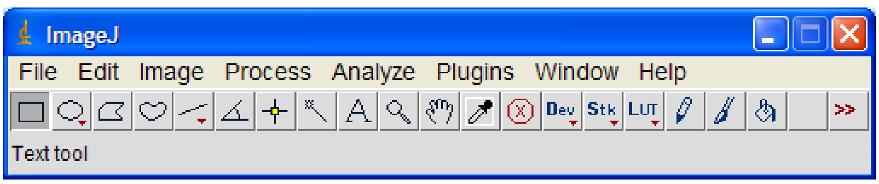
1. Image Acquisition

Image acquisition is the most important process in image processing. Capture of good quality images which are clear with known measurement using a digital camera. Images may be of differing resolutions which are 24-bit colour, 8 bit grey or 1 bit black and white.

a. Using ImageJ

Employ ImageJ and open a stored image (Figure 6.6). Select an identified section area and duplicate. The selected area is displayed in a pop-up screen. This is the image selected for analysis (Figure 6.7).

Select File $\rightarrow$ Open



b. Calibration and validation

Draw a line over the scale bar and select Analyse → Set Scale

Select Analyse → Set Scale

i. In the Set Scale window enter the 'Known Distance' box.

ii. Set the 'Unit of Measurement'

2. Image Processing

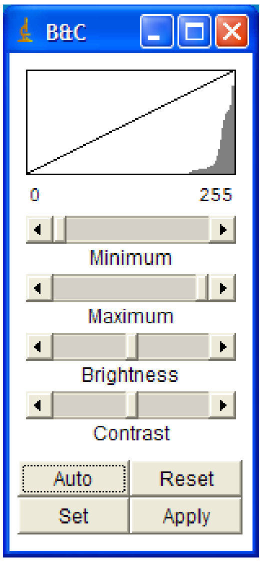
These are adjustments made to the image prior to analysis. This step involves adjustments which alter the brightness and contrast or remove dust and scratches from the image.

a. Convert the image to grayscale (Figure 6.8)

Image → Type → 8-bit

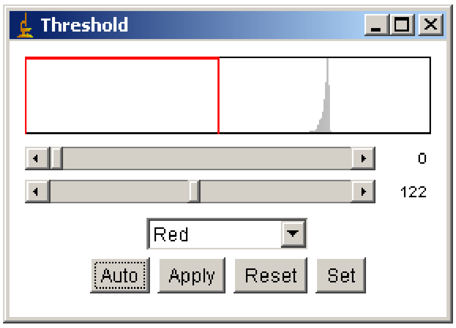
b. Adjust the brightness

Image → Adjust → Brightness and Contrast



c. Threshold the image manually using the automated routine (Figure 6.9).

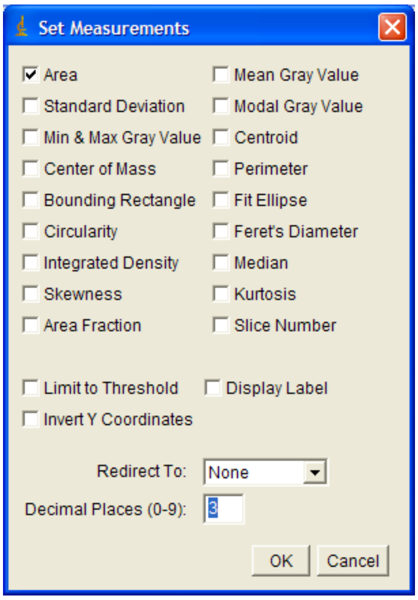
Image →Adjust → Threshold



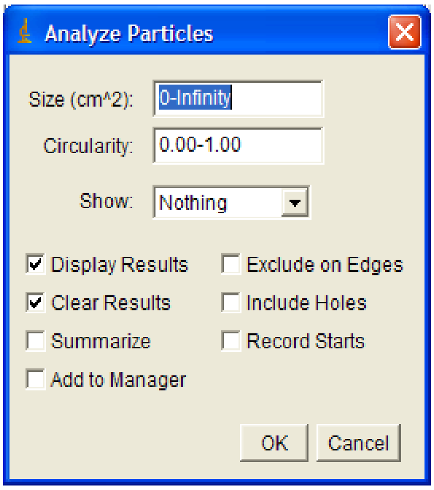
3. Image analysis

Select the measurements from the set of measurements available.

a. Select Analyse → Set Measurements.



b. Select Analyse → Analyse particles



The image of the analysed image is shown in Figure 6.10 and the measurements will be in the displayed as numbers which can be used for further analysis using an Excel spreadsheet (Table 6.1).

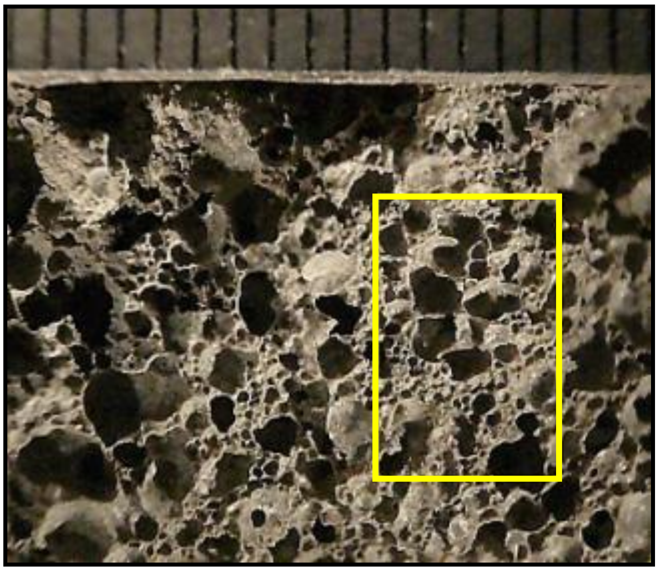


Figure 6.6: Image of a foamed concrete sample

Figure 6.7: Selected area to measure in 64 bit colour

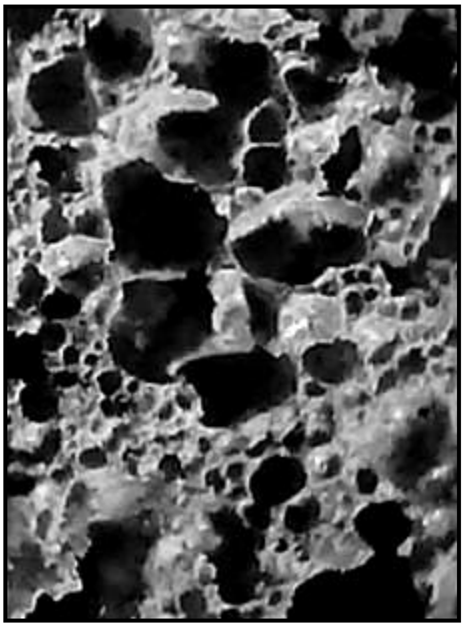


Figure 6.8: Image converted to grayscale

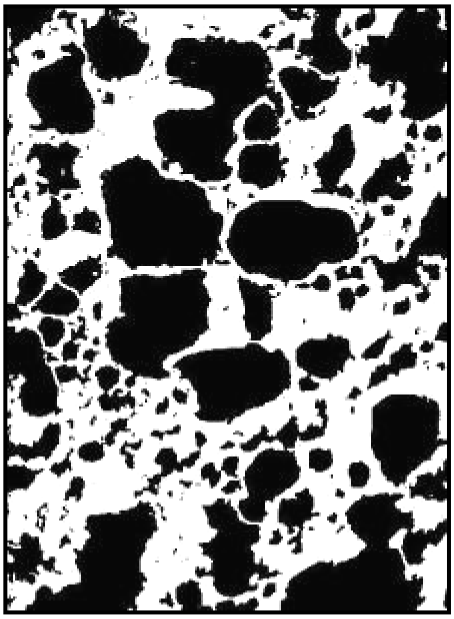


Figure 6.9: Image after brightness and threshold adjusted

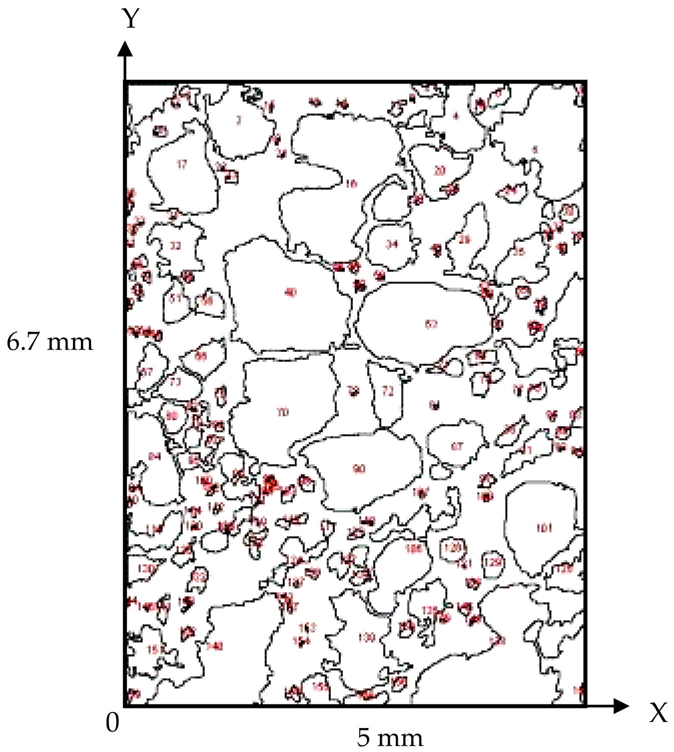


Figure 6.10: Processed image with outlines

Table 6.1: Measurements saved in Excel file

	Area (mm^2)	**X (mm)**	**Y (mm)**	**Perimeter (mm)**
1	0.498	0.417	0.385	3.957
2	0.076	1.035	0.088	1.297
3	0.01	1.87	0.05	0.457
4	5.48E-04	2.02	0.007	0.092
5	0.026	2.365	0.057	0.689
6	0.003	4.193	0.03	0.196
7	0.402	4.966	0.497	5.167
8	0.217	6.502	0.164	2.283
9	9.13E-04	4.42	0.058	0.103
10	1.312	6.077	0.797	5.289
11	3.65E-04	1.527	0.142	0.065
12	0.001	2.503	0.204	0.134

6.3 RESULTS

The purpose of the current study was to investigate the microstructure of the foamed concrete mixes of varying densities, w/c ratios, different materials constituents and combinations. The empirical values which illustrate these findings were linked to other properties for an in-depth study to achieve a better understanding of the behaviour of foamed concrete. There are possible errors in this imaging technique; the largest source of error may come from selecting the small sample which represents the characteristics of the specimen.

As previously mentioned, the terms 'voids' and 'bubbles' have been used interchangeably. Air-voids depict large, undefined and generally the inclusions in the concrete matrix not deliberate. The term bubbles are used more frequent in foamed concrete which described the features which are small and spherical; and produced from preformed foam which was intentionally included.

There were three sets of experiments. In the first set of experiments, the mixes studied employed the same constituent materials at three different densities: 600 kg/m^3, 1000 kg/m^3 and 1400 kg/m^3. Three different w/c ratios were investigated at each density, 0.40, 0.50 and 0.60. The characteristic of bubbles using synthetic surfactant was also investigated, along with the addition of wetting agent, a chemical additive. In the second set of experiments, different constituents were used at two different densities, 600 kg/m^3 and 1000 kg/m^3 at varying w/c ratios. The third experiment studied foamed concrete mixes at low density 300 kg/m^3. This set employed different cement combinations; the main cement was calcium sulphoaluminate, CSA. The results obtained were computed as analysed by the software ImageJ. All the measured area from the specimen was approximately 5 mm x 6.7 mm. The descriptions of the results are shown in Figure 6.11. The diameter in the results corresponds to the average diameter, unless otherwise stated. However, there were some samples where analyses by ImageJ were not possible due to its nature of fineness and some inconsistencies. For these mixes, descriptive explanation was clearer.

6.3.1 Set 1

Table 2 shows the results of specimens from Set 1. These results were used in Figures 6.12 and 6.13 which showed the bubble counts and bubble diameter for the selected densities at varying w/c ratios respectively. From Figure 6.12, it can be noted that there was an increase in bubble count with increase in density. However, the bubble count decreased with increase in w/c ratio. In Figure 6.13, the (mean) diameter decreased with increase in density. For each density, the diameter reduced with decreased in w/c ratio. However, in any density, the variation in bubble diameter is not clearly defined, which accounts for the small variation in Figure 6.13. Increase in density is related to increase in solids for the same volume. The higher volume of solids reduced the spaces which allowed the bubbles to increase in size and amalgamate to the bigger sizes, hence small bubble diameter was observed.

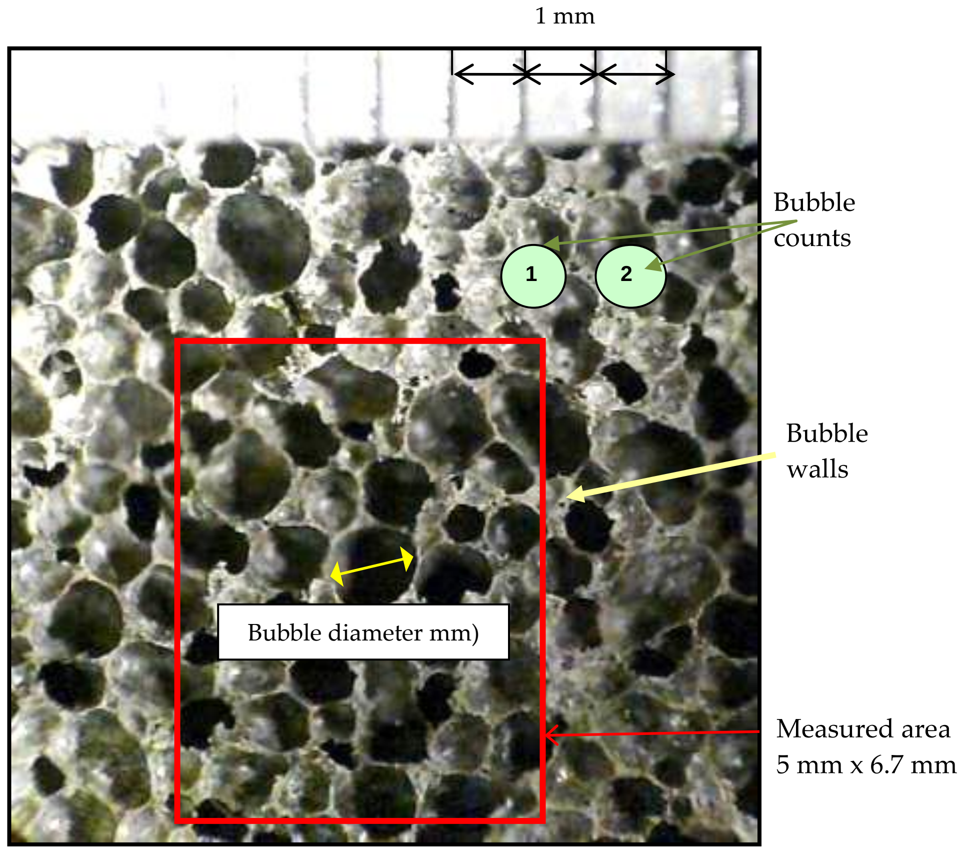


Figure 6.11: Description used in microstructure in a foamed concrete specimen

Table 6.2: Bubble details for all densities and w/c ratio for measured area

		Bubble Counts	Average Area (mm^2)	Average Diameter (mm)
Density 600 kg/m^3				
	0.40	196	0.14	0.41
w/c ratio	0.50	177	0.14	0.43
	0.60	146	0.17	0.47
Density 1000 kg/m^3				
	0.40	517	0.04	0.23
w/c ratio	0.50	339	0.06	0.28
	0.60	276	0.09	0.33
Density 1400 kg/m^3				
	0.40	820	0.02	0.16
w/c ratio	0.50	663	0.03	0.18
	0.60	523	0.04	0.21

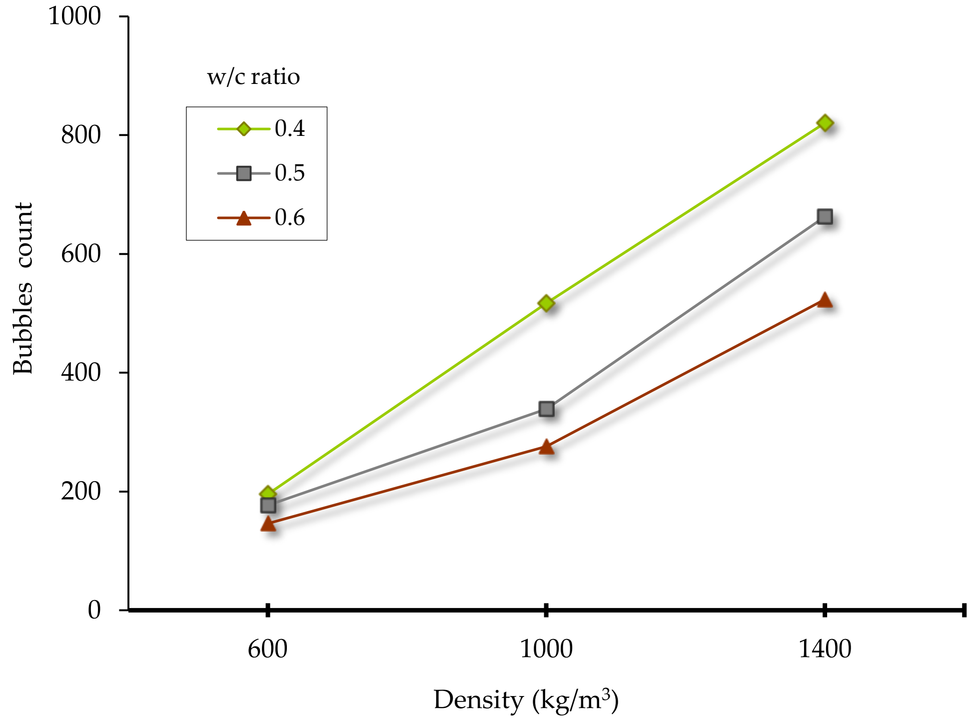


Figure 6.12: Bubbles count for different densities

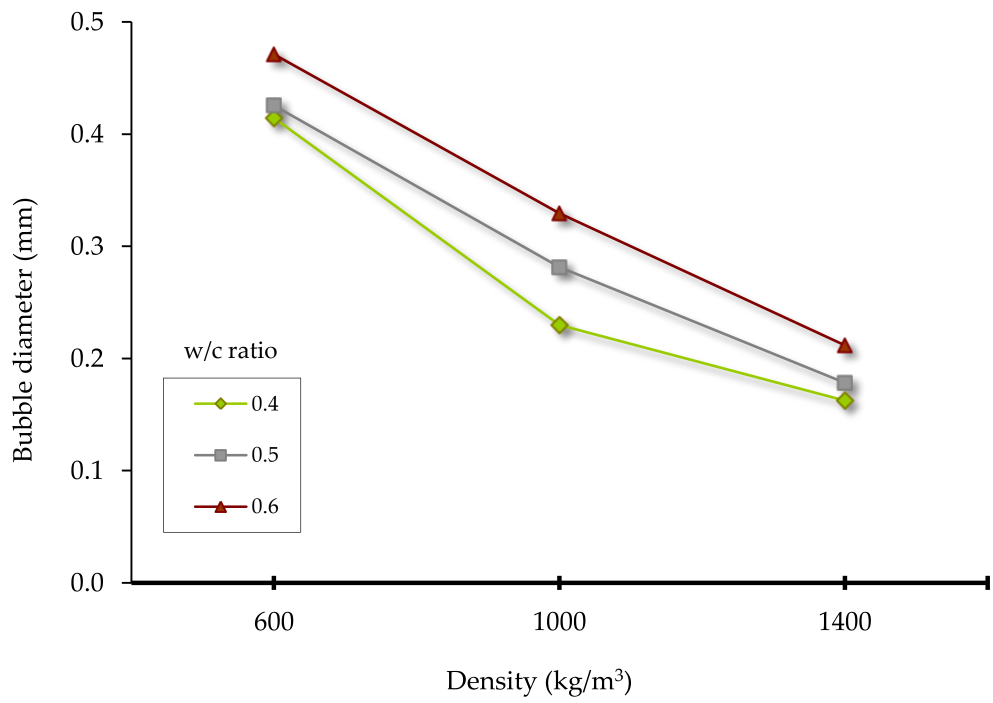


Figure 6.13: Diameter of bubbles for different densities

Figure 6.14 shows the microstructure of the foamed concrete at various densities and w/c ratios. These images are arranged using the same scale. The variation in bubble sizes for different densities is clearly shown. At low density 600 kg/m^3, the bubbles were biggest compared to bubbles in density 1000 kg/m^3 and density 1400 kg/m^3. However, the variation in w/c ratio was not clearly visible until the analyses using ImageJ. The average diameter of mixes in the higher w/c ratio was bigger compared to the average diameter in the mixes of lower w/c ratio. This trend was similar to all the densities. The bubbles in density 1400 kg/m^3 were very small, the smallest being the lowest w/c ratio at 0.4. This bubble density accounts for the stable mix which is discussed further in Chapter 7: Causes of Instability in Foamed Concrete.

Figures 6.15 and 6.16 show the comparison in bubble count and bubble diameter between the top and bottom sections of a specimen respectively. The foamed concrete mixes were cast in cylinders which were cured in an upright position. These top and bottom sections relate to the split specimen as described in Figure 6.3. The difference in bubble count was not distinctive in all densities, as shown in Figure 6.15. Figure 6.16 shows that there is a slight difference in bubble diameters at the top and bottom for density 600 kg/m^3.

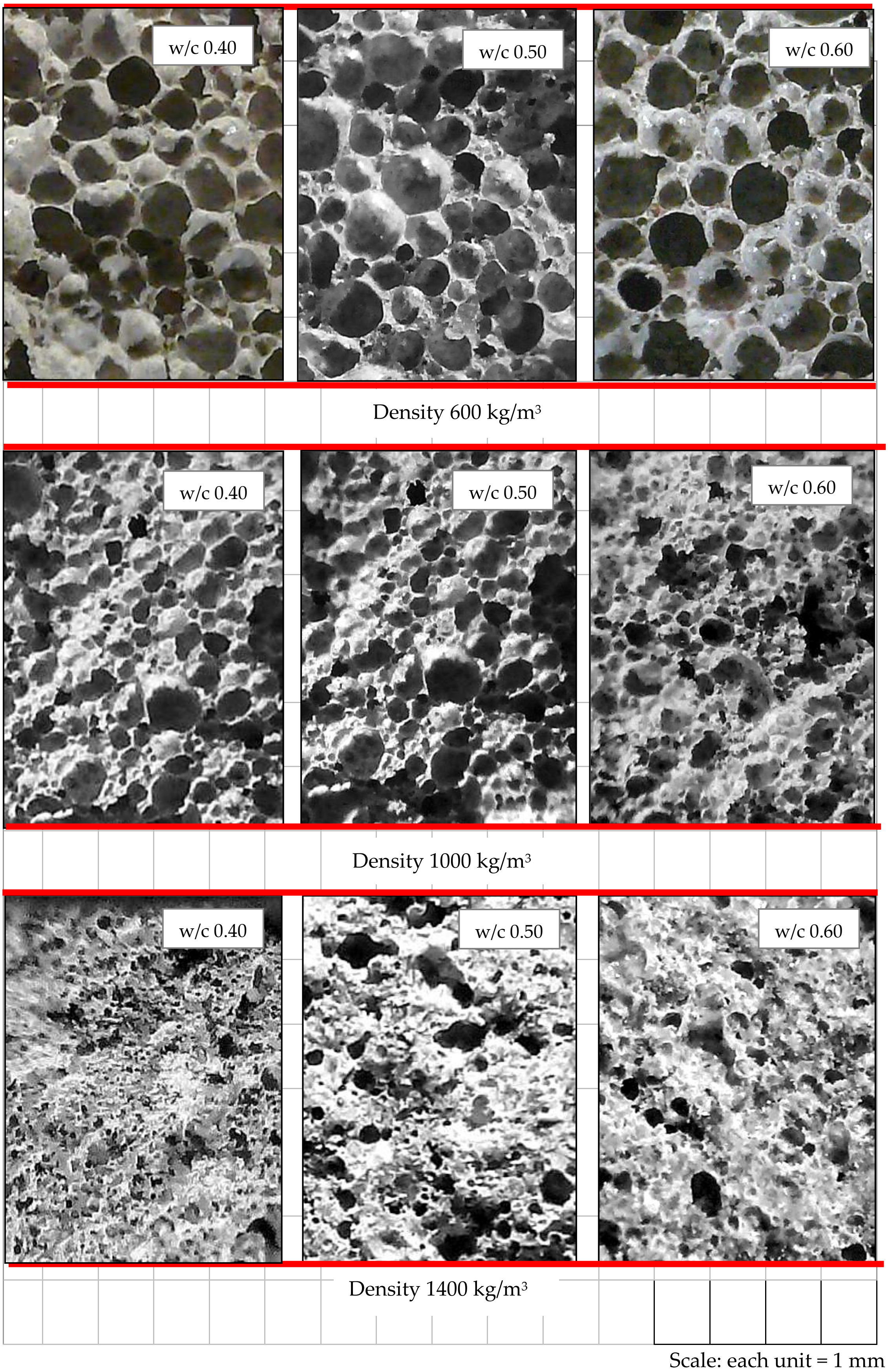


Figure 6.14: Foamed concrete bubbles of different densities and w/c ratio

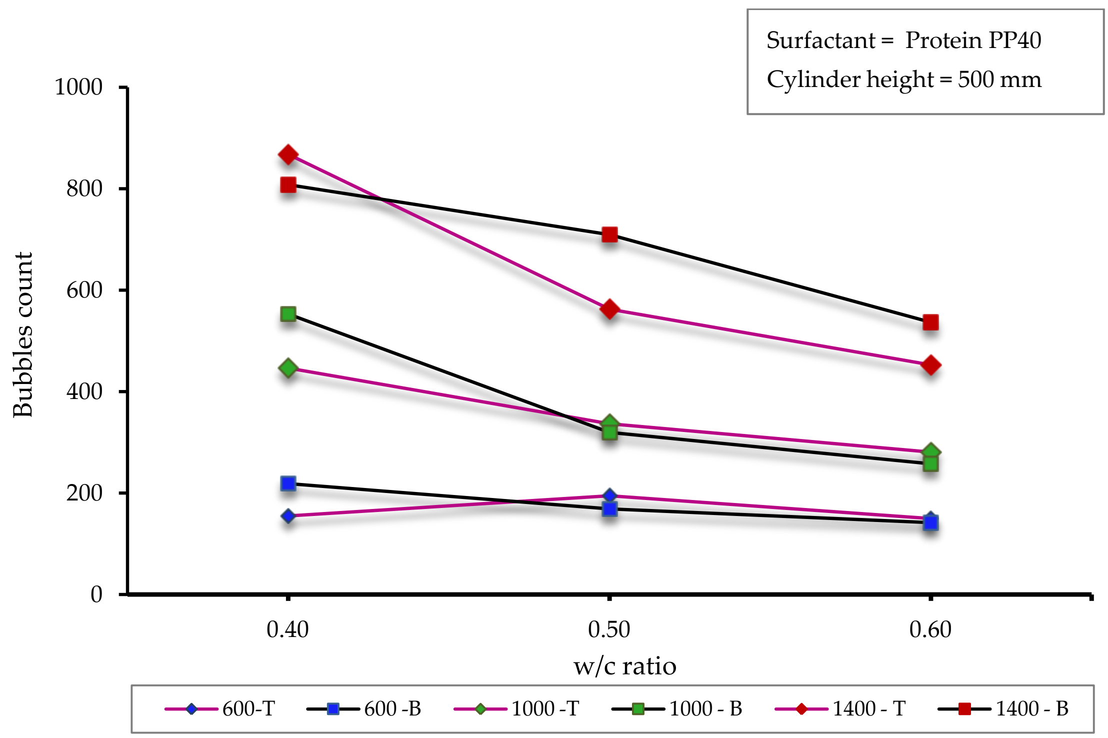


Figure 6.15: Comparing bubbles count for top and bottom specimen

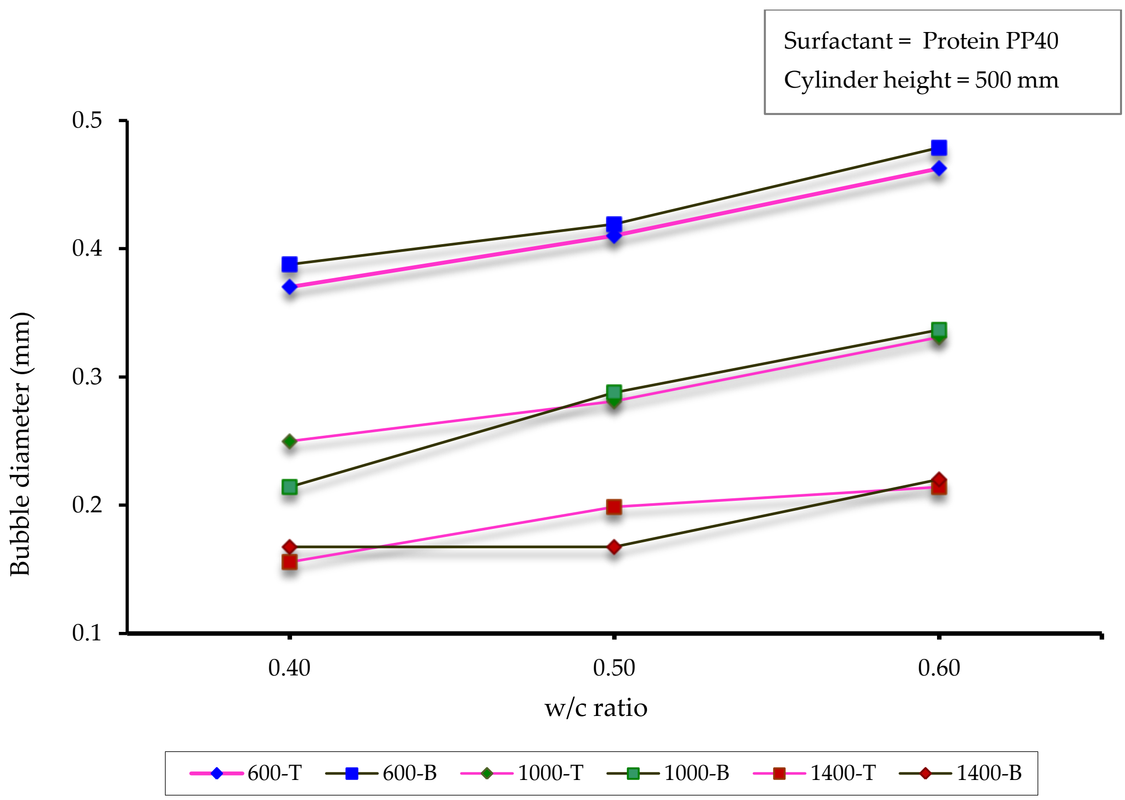


Figure 6.16: Comparing bubble sizes for top and bottom specimen

Two types of surfactants which are commonly used in the production of foamed concrete are protein-based and synthetic-based surfactants. Protein surfactant produced closed cell, stable and stronger textured bubbles which resulted in foamed concrete of higher strength (Dransfield, 2000; McGovern, 2000). In contrast, the synthetic surfactant produced larger size bubbles which have cells that are more open and this resulted in foamed concrete of lower strengths compared to protein-based surfactants (Dransfield, 2000; Highways Agency and TRL, 2001). Based on these statements, experiments were made for comparison between protein and synthetic surfactants.

Figures 6.17 and 6.18 show foamed concrete of the same density 600 kg/m^3 at w/c ratio 0.50 using different surfactants. From Figure 6.17 it can be seen that the bubbles from protein surfactants are closed and defined with connecting bubble walls. Figure 6.18 shows foamed concrete using synthetic surfactant where the bubbles are open and the bubble walls appear broken. The bubbles appear to have 'holes' or 'bubbles inside the bubbles'. This explains the 'weaker' bubbles in synthetic surfactants. Additional images of the microstructure of foamed concrete using synthetic surfactant were shown in Figures 6.19 and 6.20. These two images show foamed concrete of density 300 kg/m^3 at w/c ratio 0.50. The purpose of casting at low density was to observe the characters of the bubbles without having too many solids in the mixture. It was not possible to analyse using ImageJ since the samples appeared to have 'holes' inside the bubbles.

Wetting agent was included for a study on instability in foamed concrete as described in Chapter 7. The microstructures of the foamed concrete of density 600 kg/m^3 with inclusion of wetting agent were shown in Figures 6.21 to 6.23. The bubbles of the foamed concrete with wetting agents appeared disintegrated. The degree of disintegration appeared to have increased with the increased percentage of wetting agent. This pattern was repeated in density 300 kg/m^3 as shown in Figures 6.24 and 6.25. The disintegration of the bubbles resulted in more brittle and less sustainable foamed concrete specimens, although the surface level did not drop catastrophically. This effect will be discussed in greater detail in Chapter 7: Causes of Instability in Foamed Concrete.

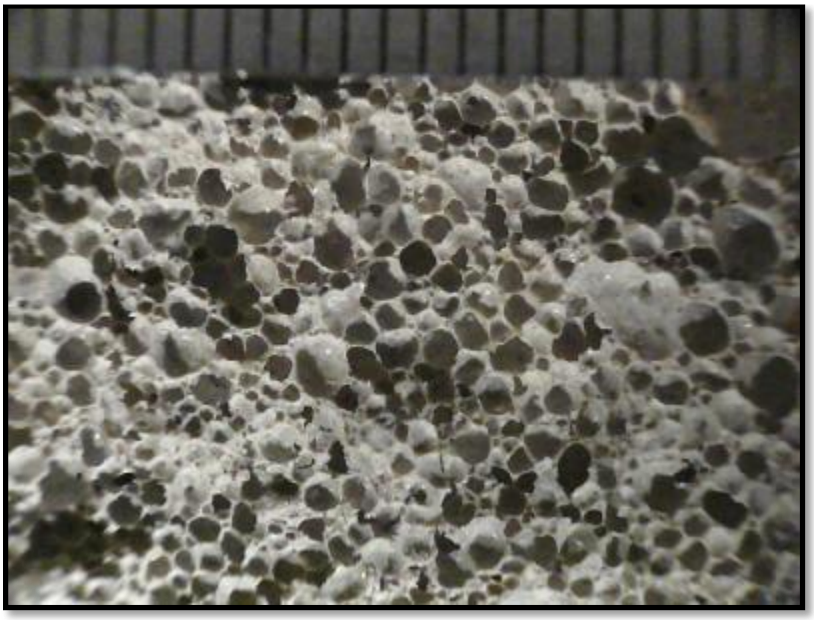


Figure 6.17: Density 600 kg/m^3 at 0.50 w/c ratio using protein surfactant

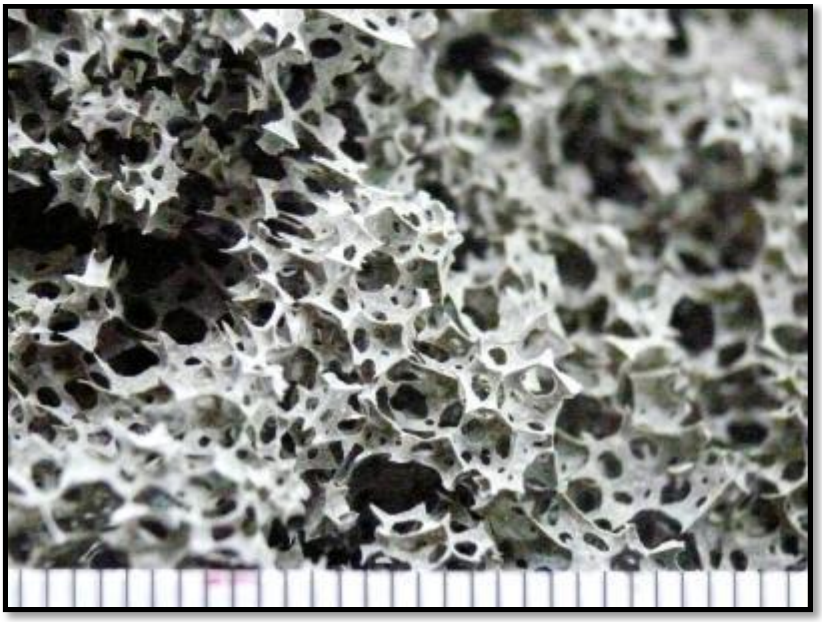


Figure 6.18: Density 600 kg/m^3 at 0.50 w/c ratio using synthetic surfactant

* Each unit in the scale presents 1 mm.

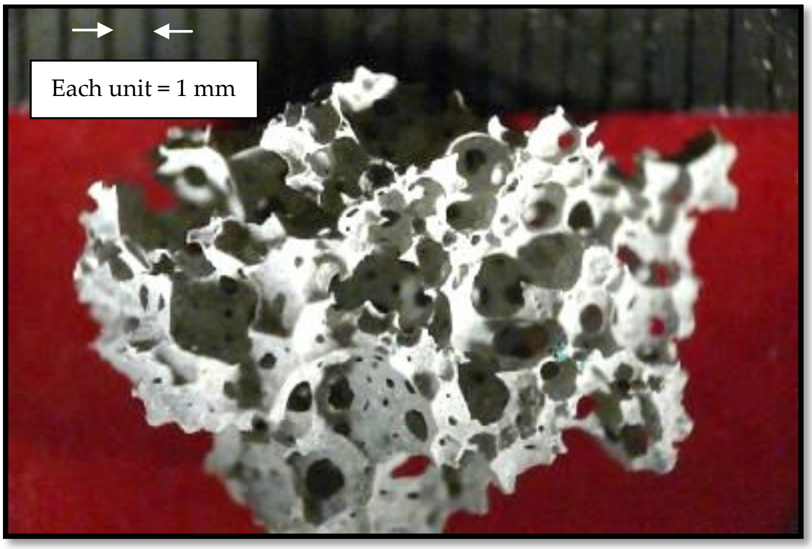


Figure 6.19: Small specimen of density 300 kg/m^3 at w/c ratio 0.50 using synthetic surfactant

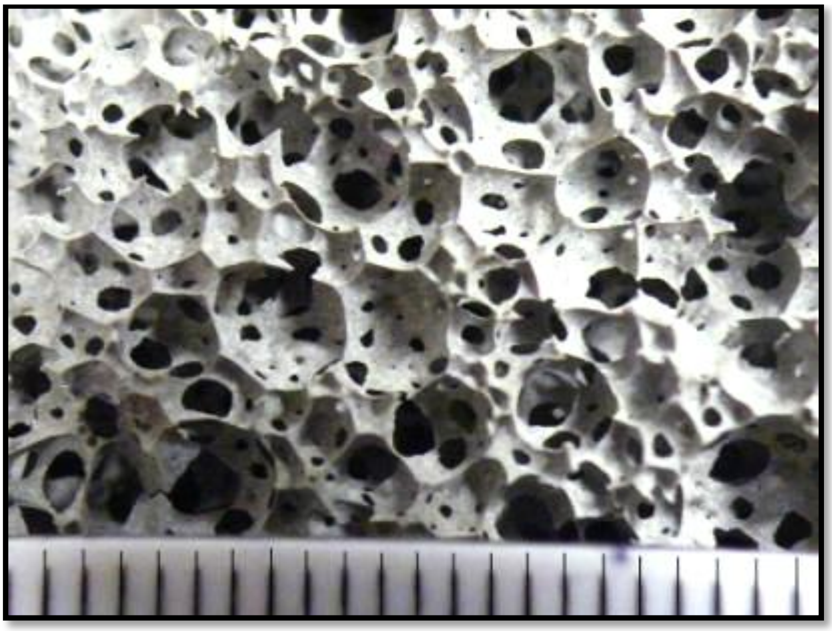


Figure 6.20: Density 300 kg/m^3, w/c ratio 0.50 using synthetic surfactant

* Each unit in the scale presents 1 mm.

Figure 6.21: Density 600 kg/m³ at w/c ratio 0.50 without wetting agent

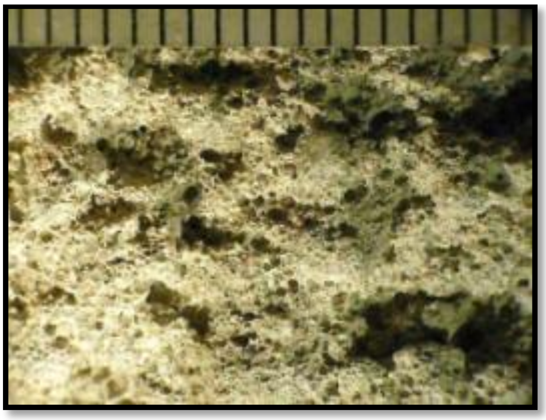


Figure 6.22: Density 600 kg/m³ at w/c ratio 0.50 with 1% wetting agent

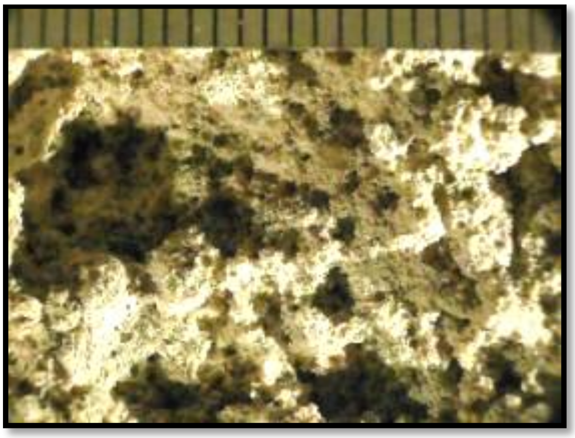


Figure 6.23: Density 600 kg/m³ at w/c ratio 0.50 with 2% wetting agent

* Each unit in the scale presents 1 mm.

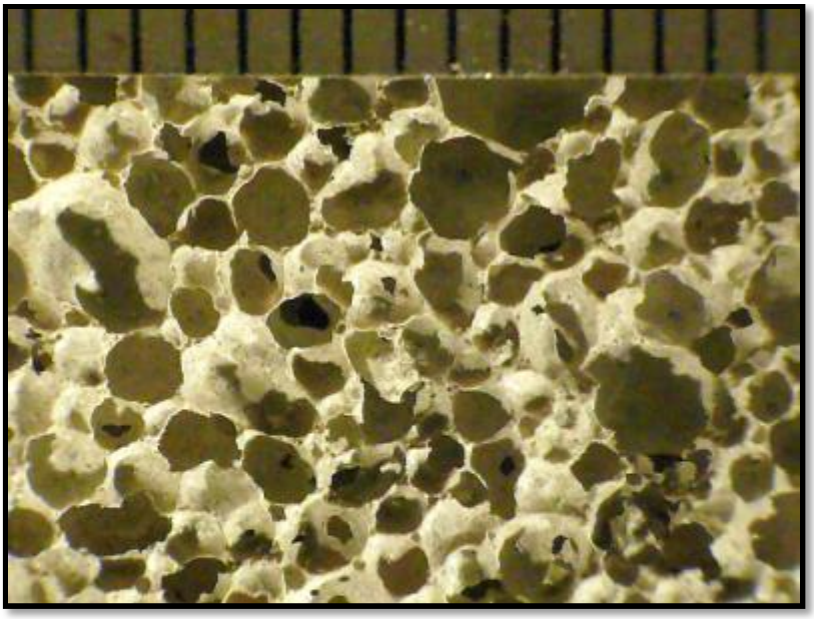


Figure 6.24: Density 300 kg/m^3 at w/c ratio 0.50 without wetting agent

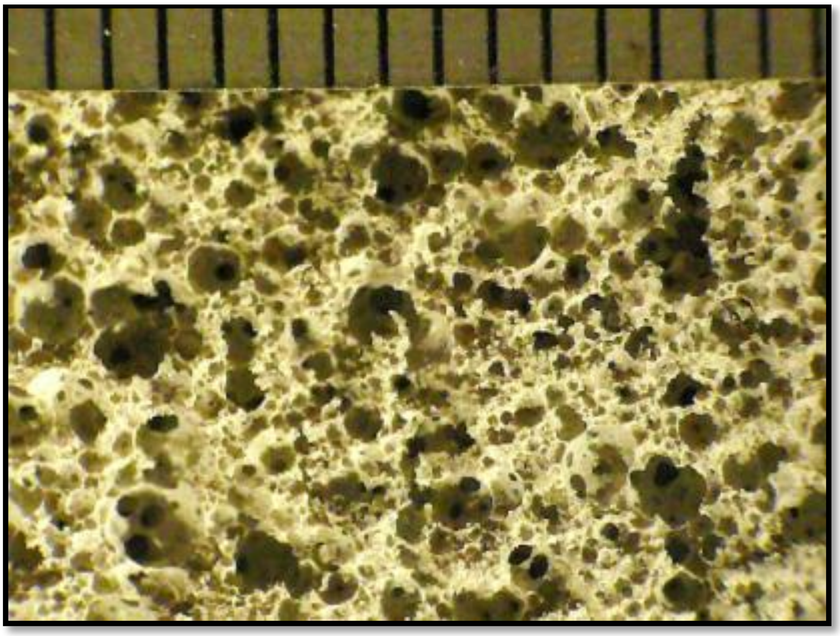


Figure 6.25: Density 300 kg/m^3 at w/c ratio 0.50 with 1% wetting agent

6.3.2 Set 2

In Set 2, the densities were 600 kg/m^3 and 1000 kg/m^3, with various w/c ratios. For foamed concrete mixes at density 600 kg/m^3, the variations were cement fineness and filler fineness, whilst for the 1000 kg/m^3 density, the variation in the mixes was only for cement fineness. For both cement and filler variations, the range of w/c ratios was between 0.4 to 0.8. Some of the microstructure can be observed and analysed using ImageJ but some specimens collapsed and analysis was not possible using ImageJ. For these specimens, the microstructure is described below.

In another study, the microstructure of the foamed concrete mixes, bubbles size distribution was adopted to obtain the values of d10, d50 and d90 from analysis of the images. The values of d50 and d90 reduced as the cement fineness increased, as shown in Figure 6.26. By replacing 30% of CEM I 42.5N with fine fly ash, (FA_f) the values of d90 were halved. When metakaolin replaced 20% of CEM I 42.5N, the d90 was reduced to a third. The values of d50 were also reduced when replaced with finer cements; FA_f and metakaolin. However, the trend of d10 was not similar to that of d50 and d90.

A similar trend was observed when the fineness of filler was increased. The values of d50 and d90 were reduced when the filler fineness was increased by replacing fine aggregate with coarse fly ash (Figure 6.27). With 50% fine aggregate replacement, the d90 value was reduced to more than half of the value of d90 for fine aggregate only. With 100% total replacement, the value of d90 was reduced to a third. Consequently, the value of d50 was also reduced when fine aggregate was replaced with coarse fly ash.

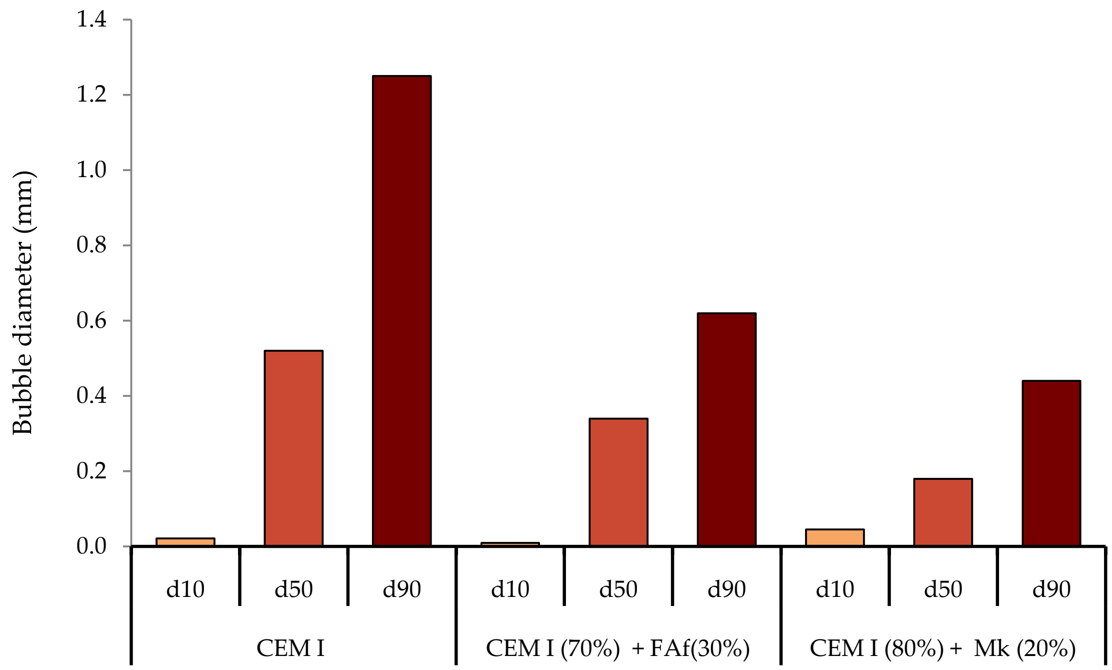


Figure 6.26: Bubble diameters of density 600 kg/m³ specimens with varying cement fineness

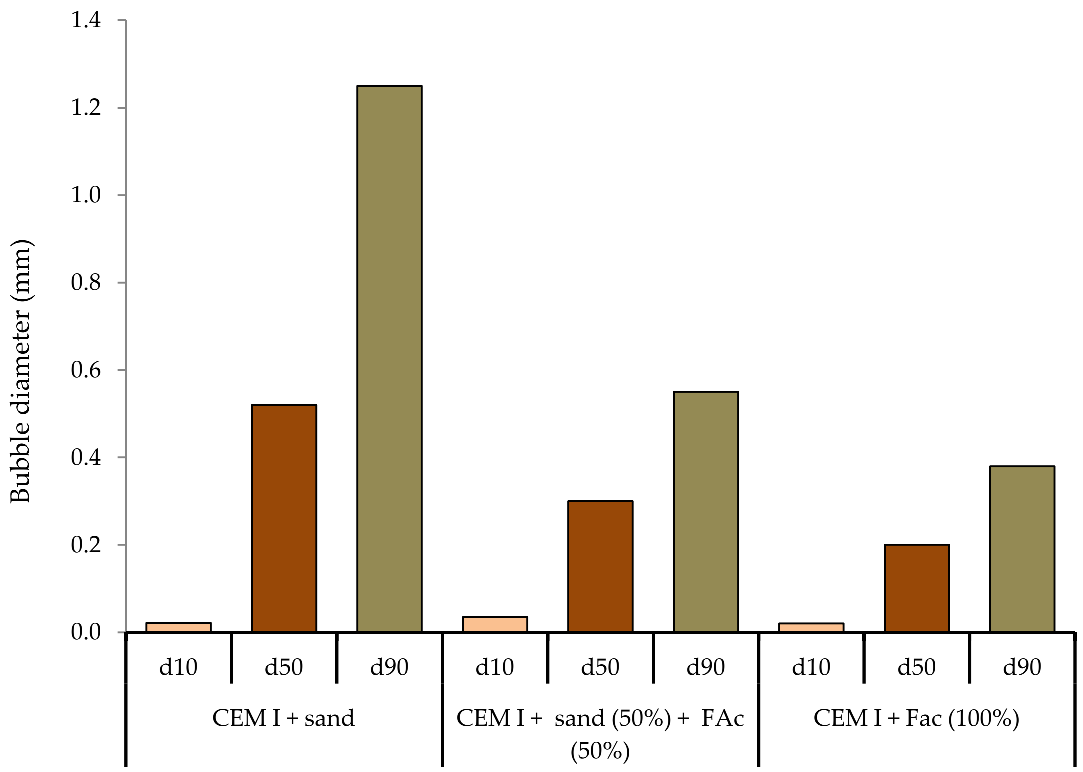


Figure 6.27: Bubble diameters of density 600 kg/m³ with varying filler fineness

For the higher density 1000kg/m^3 in Set 2, the foamed concrete variations were the cement fineness whilst the filler was invariable: the fine aggregate. The percentage replacement was repeated, where 30% CEM I 42.5N was replaced with fine fly ash in the second mix, and 20% CEM I 42.5N was replaced with metakaolin in the third mix. The bubble diameters reduced when the fineness were increased, as shown in Figure 6.28. For foamed concrete mixes at density 1000 kg/m^3, all the bubble diameters were less than 0.35 mm, which accounts for no drop in level for all the mixes in this density; hence no instability issues. The relationship between the bubble sizes and instability will be further discussed. The third foamed concrete mixes were sticky at lower w/c ratio and bubble analysis was not possible as they were erratic.

6.3.3 Set 3

In Set 3, where the main cement was CSA, the combinations were different proportions with CEM I 52.5R and another set of combinations with fly ash, FA. For the first combination, there were three different proportions in blend of CEM I 52.5R and CSA (Figures 6.29 to 6.32). In the 100% CEM I 52.5R, the bubbles were clearly defined and spherical. With 20% CSA replacement, the bubbles became smaller in size, although the sphericity was still obvious (Figure 6.30). The bubbles became less distinctive with additional replacement of CSA; a total of 40% (Figure 6.31). With further replacement totalling to 50% of CSA, the bubbles appeared to have reduced in number and seemed less spherical (Figure 6.32). However, in all four cement combinations, the foamed concrete mixes remained stable, which was crucial in the study of instability, as discussed in Chapter 7: Causes of Instability in Foamed concrete.

In the second combination, CSA and FA were blended at different proportions. FA, as widely known, is a waste product; hence economically viable if replacement produces an end-product with the same characteristics. The blend of CSA and FA at different proportions of 60:40, 50:50 and 30:70 were found to have produced stable foamed concrete mixes. On their microstructural characteristics, there was no distinct characteristic difference in the various proportions of the mixes (Figures 6.33 to 6.36). In all the mixes, the bubbles appear small and barely spherical. These undefined characteristics were repeated in all w/c ratios.

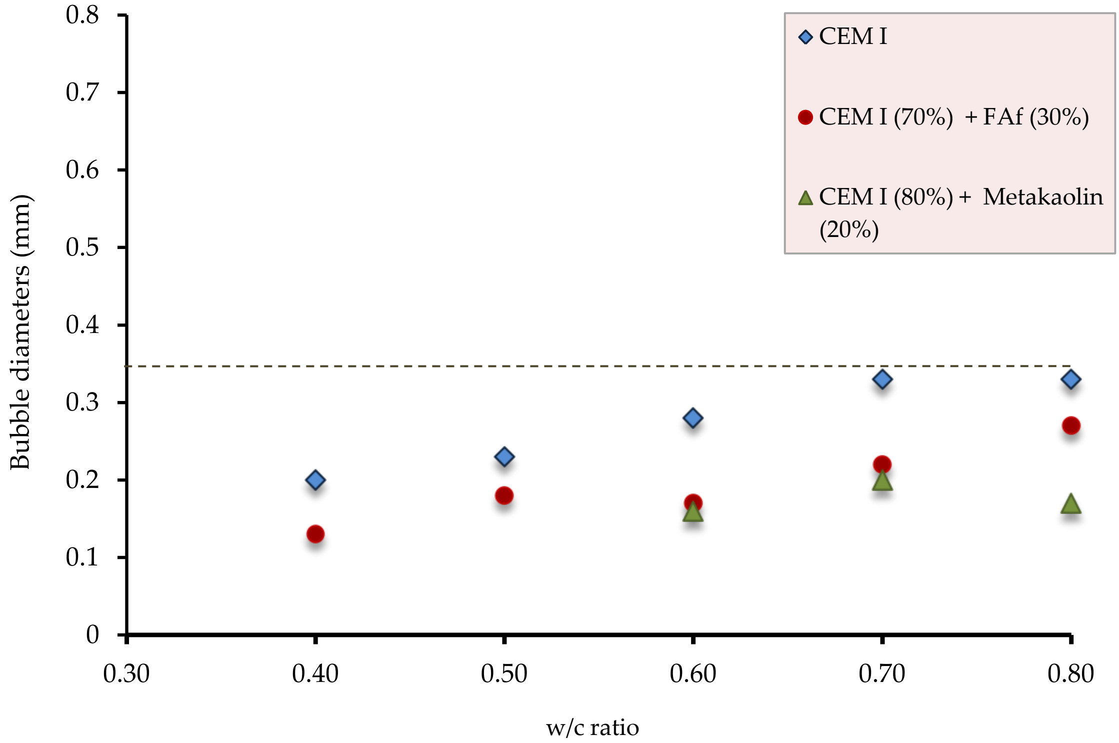


Figure 6.28: Bubble diameters for density 1000 kg/m³ of varying cement fineness

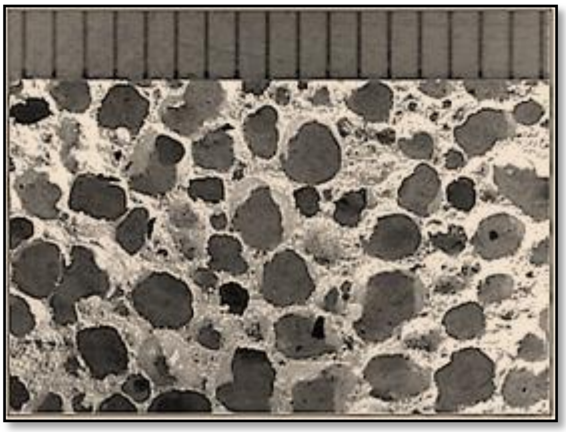


Figure 6.29: 100 CEM I 52.5R (w/c ratio 0.50)

Figure 6.30: CEM I 52.5R : CSA / 80: 20 (w/c ratio 0.50)

Figure 6.31: CEM I 52.5R : CSA / 60: 40 (w/c ratio 0.50)

Figure 6.32: CEM I 52.5R CSA / 50: 50 (w/c ratio 0.50)

Figure 6.33: CSA:FA 60:40 (w/c ratio 0.50)

Figure 6.34: CSA:FA 50:50 (w/c ratio 0.50)

Figure 6.35: CSA FA/ 40:60 (w/c ratio 0.50)

Figure 6.36: CSA FA / 30:70 (w/c ratio 0.50)

6.4 SUMMARY OF RESULTS

In this chapter, the study on the microstructure of foamed concrete was conducted by examining the factors that affected the structure and by observing its relationship with rheological properties and instability. This phase of the study revealed that several factors determine the microstructure of foamed concrete and it was not clear which had the most influence. The determining factors were the density, w/c ratios, constituent materials, their proportions and chemical additions. This study was confined to empirical results without in-depth analysis of the chemistry, although some assumptions were made based on their incompatibilities.

The significant outcomes from this phase of the study are:

1. An increase in density produced a decrease in bubble size but an increase in bubble count. Correspondingly, an increase in w/c ratio of the same density reduced the bubble count whilst the bubble size increased. With the same constituent materials, the lower density produced bigger bubbles and, inversely, the higher density produced smaller bubbles.

2. Protein surfactant produced spherical, more defined and closed bubbles which were not connected. Synthetic surfactant formed bubbles that were 'open', undefined, with 'holes' in their cells.

3. For the same density and w/c ratio, the bubble sizes decreased with increase in either the cement fineness or the filler fineness. These were obtained using protein surfactant.

4. The addition of wetting agent to foamed concrete mixes disintegrated the bubbles. Although it improved the occurrence of collapse, the foamed concrete was weak and fractured easily.

5. Generally, using the same constituent materials, foamed concrete mixes at higher densities (> 1000 kg/m^3) did not drop more than 5% in height; hence they were construed as stable.

The bubbles were spherical and small, with d50 less than 0.3 mm. Foamed concrete mixes of 600 kg/m^3 experienced some occurrences of collapse. There were clear big bubbles; notably with d90 greater than 1mm.

6. For foamed concrete mixes of density 300 kg/m^3, using cement type CEM I 42.5N, the episodes of collapses were frequent. Conversely, using cement type CEM I 52.5R (fast setting cement), the foamed concrete mixes were stable. Stability was achieved with CSA cement and blends of CSA and CEM I 52.5R and CSA and FA_f.

CHAPTER 7: CAUSES OF INSTABILITY IN FOAMED CONCRETE

7.1 INTRODUCTION

The main characteristics of foamed concrete are the low self-weight, ability to flow and self-levelling properties which it possesses in its hardened and fresh state. Ideally, foamed concrete has to possess high flowability properties to ensure that it reaches the target destination, yet stable enough to resist the high strain rates generated by the flow. However, these are only beneficial if the material is stable with no segregation. Segregation, of foam concrete may alter these characteristics, hence, nullifying the objective of using this innovative form of concrete.

Low density foamed concrete is currently in demand in the construction industry. As reported within this section, projects which in the past have utilised foamed concrete, have typical deployed densities which were higher, when compared to those which have been used in recent years. The first of these projects was the widening and strengthening project of the Kingston Bridge, London, completed in 2001 (Figure 7.1). In this project, the foamed concrete density was 1400 kg/m^3. The second project is a mine stabilisation project in Combe Down, Bath, which started in 2001, where foamed concrete with a density of 600 kg /m^3 was, used (Figure 7.2). The third and most recent project, involves topping up the structural infill for a tunnel at Gerrards Cross, London which began in November 2009. In this project, the foamed concrete density utilised was a low as 400 kg/m^3.

These examples emphasises the concrete industries continued trend in utilising lower density foamed concretes. However, achieving the ability to maintain a stable low self-weight continues to present a challenge to the industry. Low self-weight corresponds to a high percentage of air which is obtained by inclusion of a high amount of preformed foam. The stability of the foam is a function of density and the type of surfactant employed (Highways Agency and Transport Research Laboratory, 2001). By contrast, the instability of the foam can be induced by a number of external environmental factors, which include; temperature, humidity, alkalinity or acidity. Internal factors can also affect instability. These internal factors include; incompatibility of the foamed concrete with other materials such as chemical admixtures, and other constituent materials, such as GGBS and fly ash (Highways Agency and

Transport Research Laboratory, 2001; Jones, 2001, Jones and McCarthy, 2005c). The instability of the foam causes the bubbles to collapse which alters the density of the concrete, and consequently, this affect both the fresh and the hardened properties. Consequently, this characteristic has an effect on both the fresh state properties and the hardened properties of the foamed concrete. This unpredictability can be an unfavourable feature of foamed concrete and has occurred under the same conditions using the same constituent materials in practice, as illustrated in Figure 7.3 and Figure 7.4.

The aim of research presented in this thesis was to study the parameters that lead to instability in foamed concrete. Other parameters that are possibly linked to foamed concrete instability include density, w/c ratio, constituent materials and its proportions. The experimental programme and the methodology were described in the following sections.

Figure 7.1: Widening and strengthening of Kingston Bridge, West London

(http://www.lobeg.com/index.php?option=com_content&view=article&id=5&Itemid=13, November 2010)

Figure 7.2: Combe Down mine stabilization project

(http://www.foamedconcrete.co.uk/studies_combe.php, January 2010).

Figure 7.3: Stable foamed concrete in Gerrards Cross project

(Courtesy of Propump Engineering Ltd, UK)

Figure 7.4: Collapsed foamed concrete in Gerrards Cross project

(http://www.foamedconcrete.co.uk/news1.php, January 2010)

(http://www.nce.co.uk/news/geotechnical/cross-purpose/1995578.article, January 2010)

7.2 MATERIALS, EXPERIMENTAL PROGRAMMES AND METHODOLOGY

7.2.1. Introduction

Appraisal of the instability of foamed concrete especially at lower densities indicated that there were several factors, rather than any single cause, which contributed to the instability of foamed concrete (Highways Agency and TRL, 2001). No standard test to investigate instability existed. Nevertheless, it was noted that assessment of instability within foamed concrete could be achieved by visual observation of the consistency of mix (McCarthy, 2006; Jones and McCarthy, 2005c; Nambiar and Ramamurthy 2007a). Adopting this technique in the current study, the drop in the surface level was assumed to have resulted from instability within the foamed concrete.

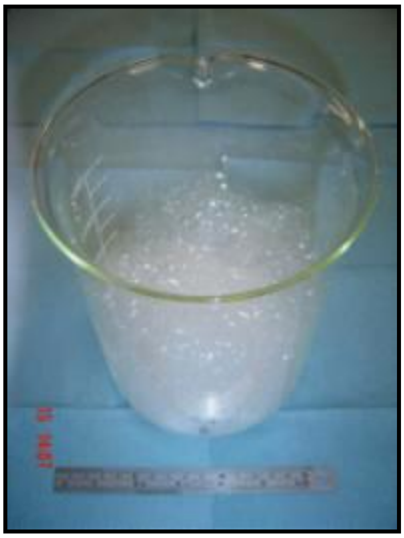
In the current study, it was observed that under normal laboratory conditions, preformed foam collapsed easily, as shown in Figure 7.5 (1 - 6). Observations on the progressive collapse of a synthetic-based foam were taken over a time period of approximately 1 minute 30 seconds. Based on this fragility, 'dropout' tests were done to study whether various conditions had any effect on the speed of collapse of preformed foam. The conditions included varying external humidity and temperature. For the study on stability of foamed concrete, few possible factors were investigated in this study, as illustrated in Figure 7.6. Primarily, the bubbles, produced from the surfactants were varied using two different surfactants: protein and synthetic surfactant. Consecutively, the density and the w/c ratio were altered by varying the proportions. These proportions were varied using the same or different combinations of constituent materials. Recognizing that cement as the main constituent may produce different results, several cement types were selected with varying setting times and fineness. The different cement types and blends of cementitious materials were CEM I 42.5N, CEM I 52.5R, Calcium sulfoaluminate (CSA), Rapid Hardening Portland Cement (RHPC), metakaolin, and fine fly ash, FA_f. The inclusion of calcium chloride, $CaCl_2$ and wetting agent to the cement were aimed to alter the setting times. A slight variation of fillers was included by replacing sand with different percentages of coarse fly ash, FA_c, since the latter has greater fineness. Varying heights of cylinders were incorporated to study the rate of drainage and the effect of pressure arising from different heights.

1. (0 second)

2. (16 seconds)

3. (27 seconds)

4. (45 seconds)



5. (57 seconds)

6. (90 seconds)

Figure 7.5: Progressive collapse in preformed foam at 0, 16, 27, 45, 57, 90 seconds (in laboratory condition)

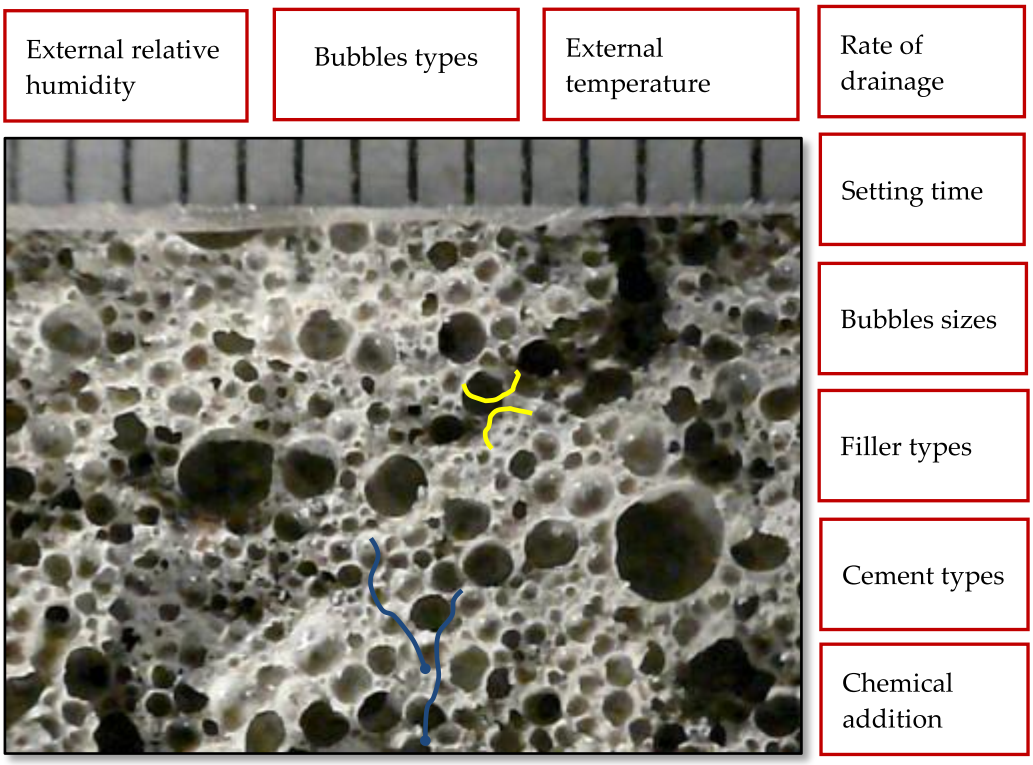


Photo: Foamed concrete mix density 600 kg/m³ at w/c ratio 0.70 using 80% CEM I 42.5N + 20% Metakaolin + sand

Figure 7.6: Parameters considered in the study of instability

7.2.2. Constituent Materials

1. Portland cement PC, CEM I 42.5N conforming to BS EN 197-1 was the main cement employed in the study. In Set 3 study, CEM I 52.5R was employed.

2. 'Fine' fly ash (FA_f) with a 45 μm sieve retention of 7.5%, loss on ignition (LOI) of 5.0% and conforming to BS EN 450.5 was used to replace CEM I 42.5N at 30% by mass fraction.

3. Metakaolin used as replacement for cement to a level of 20% in the second study (Set 2).

4. Calcium sulphoaluminate (CSA) was employed in the Set 3 study. CSA is a quick setting and early strength cement, which is finer and lighter in colour compared to CEM I 42.5N.

5. Natural sand, fine aggregate (conforming to BS EN 12620:2002 with particles greater than 2.36 mm removed by sieving).

6. Coarse fly ash, FA_c with a 45μm sieve retention of 36.0% and conforming to BS 3892-2/ BS EN 450 and ASTM C 618-94a Class F was used as 50% and 100% replacement for sand.

7. The surfactants used in this study were a protein-based surfactant – type Propump 40 and three types of synthetic surfactants – Propump Synthetic, TFAL -3 and Regular 3%. The TFAL-3 and Regular 3% surfactants were examined briefly as opposed to the Propump 40 and synthetic surfactants which were used more widely in the current experiments. The preformed foam was prepared from a 6% aqueous surfactant solution in a dry system generator with density between 40 and 50 kg/m^3.

8. The mixing water used conformed to BS EN 1008 Mixing water for concrete. In this study, the w/c ratio was varied from 0.40 to 0.80.

9. Calcium chloride (Calcium chloride anhydrous granular) in addition up to 2% and 4% cement content.

10. A commercially available wetting agent.

Table 7.1: Different conditions in dropout tests

		SURFACTANT SOLUTION	CONDITION
1.	Laboratory condition	Typical surfactant solution	Laboratory condition: 20^0C to 22^0C
2.	99% relative humidity	Typical surfactant solution	Laboratory condition: 20^0C to 22^0C Humidity: 99%
3.	High temperature solution	High temperature water (60^0C) mixed with surfactant	Laboratory condition: 20^0C to 22^0C.
4.	Deionised water	Deionised water mixed with surfactant.	Laboratory condition: 20^0C to 22^0C.
5.	High temperature condition	Typical surfactant solution	High temperature oven at 50^0C
6.	Acidic solution	Acidic water (pH 5) mixed with surfactant.	Laboratory condition: 20^0C to 22^0C
7.	Sealed in oven	Typical surfactant solution	Tightly covered in container, placed in high temperature oven at 50^0C

7.2.3. Experimental Programme

There were two main sets of experiments performed in this research, as shown in Figure 7.7: Experimental programme. These experiments were done in four phases: firstly, the dropout test and then tests on Set 1, Set 2 and followed by Set 3. The drop-out test was done on preformed foam, which studied the effect of different conditions on the amount of drop-out from the different surfactants.

The main differences between Set 1 and Set 2 were the constituent materials. In Set 1, there was a consistent set of constituent materials: CEM I 42.5N and filler types and a brief variation of surfactants. The experiments were designed to examine different densities, w/c ratios and the effect of calcium chloride and wetting agents on the mixes. In Set 2, the variations were the CEM I 42.5N and filler types, including varying their proportions which helped to consider the effect of different fineness. In addition, the foamed concrete mixes utilised in this part of the research, studied the effects of incorporating calcium chloride into the concrete, which accelerates cement hydration. In this set, the variation in cylinder heights was also included to study the effect of height on the instability. In the final set of foamed concretes, Set 3, the cement used was 52.5 grade Portland Cement (CEM I 52.5R), Calcium sulphoaluminate, CSA and blends of fly ash, FA. A single foamed concrete density of 300 kg/m^3 was investigated in this part of research.

7.2.4. Methodology for instability

Based on the experimental programme, there were four parts to the study. The dropout tests were conducted as the initial study. In the second part, a group of mixes with one set of constituent materials was studied at different densities and w/c ratios. The third part comprised of foamed concrete mixes with different constituents at fixed density and w/c ratio, whilst the fourth set studied different set of cements at low density 300 kg/m^3.

1. Preparations of specimens

Using a Hobart mixer, the foamed concrete was produced in the laboratory by adding preformed foam to the base mix, which comprised cements, fillers and water. These constituents were then mixed until a uniform consistency was achieved. The plastic density was measured in accordance with BS EN 12350-611 by weighing a foamed concrete sample in a pre-weighed container of a known volume. A tolerance on plastic density was set at ±50 kg/m^3 of the target value.

The specimens were then cast in cylinder moulds lined with domestic plastic 'cling' film. The cylinders were made of clear Perspex which allowed for visual observations. The height of the cylinder moulds varied from 70 mm to 500 mm while the diameter was 75 mm throughout the length. Once the cylinder was filled, the surface was covered with plastic cling film to prevent dehydration. After 24 hours, the level of the specimens was observed and any drop in level of the surface was recorded.

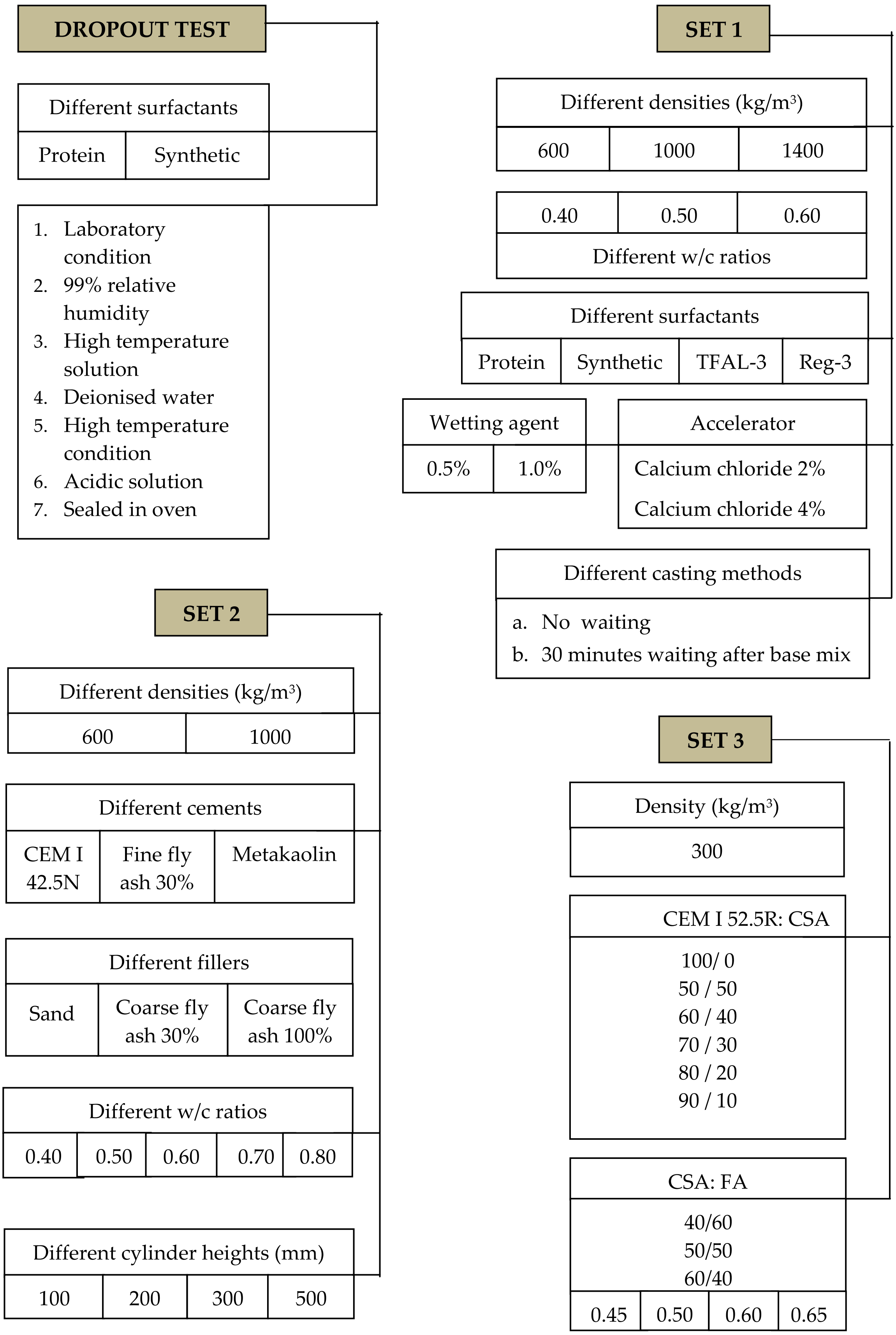


Figure 7.7: Experimental programme

Dropout test

The dropout test investigated the link between the preformed foam, a constituent in the mix and the end product, foamed concrete. The behaviour of foams which break down easily suggested that this fragility affected the stability of foamed concrete since foam constitutes a major percentage in the mix. As shown in Figure 7.5, the preformed foam collapsed catastrophically within one minute. Using this concept, the dropout test measured the amount of liquid which resulted from the collapse of the foam within a specified time, when the foams were formed and placed under various conditions.

One litre of foam was placed in a glass jar and after 20 minutes, the amount of dropout water was measured. The preformed foam was typically prepared from a surfactant solution consisting of one part surfactant to between 5 and 40 parts of water in a dry system generator. The consistency was similar to that of shaving foam at a density of between 20 and 90 kg/m^3 (Highways Agency and TRL, 2001). Typical density of a protein-based surfactant is 50 kg/m^3.

In the drop-out tests, the variations in preparation of surfactants are as in Table 7.1 as illustrated previously.

Instability test for Set 1, Set 2 and Set 3

The mix proportions of foamed concrete were carried out as described in Section 3.4 using a Hobart mixer. The mixing method employed the typical method as mentioned in Section 3.6, except for a small variation in Set 1, where the foam was added 20 minutes after the 'base mix' which was then mixed uniformly. The variations are shown in the experimental programme (Figure 7.7).

The plastic density of all the foamed concretes were measured in accordance to BS EN 12350-611 as described in Section 3.6. Then the instability of the foamed concrete was measured by casting the concrete into cylinders of varying heights. The level of the top surface was marked at the time of placing. After 24 hours, the new level was marked and any difference in the level was recorded as the amount of drop.

7.3 RESULTS

7.3.1. Dropout tests

The purpose of these experiments was to study the constituent materials in foamed concrete mixes since these have a strong influence on the behaviour of these mixes. Prior to commencement of the experiments on foamed concrete mixes, dropout tests were carried out to determine the effect of preformed foam on foamed concrete. In the dropout tests, two types of surfactants were used: the protein PP40 and synthetic surfactant. Experiments were conducted under various conditions and the amount of dropout was collected. Table 7.2 shows the quantity of dropout for the two surfactants.

The amount of dropout was highest in condition 5, where the preformed foam was placed at high temperature, 50^0C for synthetic surfactant and in condition 7, sealed in oven for protein surfactant. This was because the surface tension of bubbles decreased with increase in temperature. The high in temperature accelerated foam collapsed and led to most dropout. The least dropout for both surfactants was found in condition 4, where deionised water was used to produce the preformed foam. Deionised water had its mineral ions and other water impurities removed. These impurities interfered with the stability of the foam.

The pattern of dropout in the various conditions was similar in both surfactants, although the quantity was higher in the synthetic surfactant under all conditions (Figure 7.8). Less water drainage shown by protein surfactant was expected because protein surfactants produced more stable, stronger, yet smaller bubbles with closed cells structure compared to synthetic surfactants.

Table 7.2: Amount of dropout for different conditions

Conditions	Dropout per litre (ml)	
	PP40	**Synthetic**
1. Laboratory condition	16.2	23.3
2. 99% RH	18.7	26.3
3. High temperature solution	16.8	24.2
4. Deionised water	16.2	22.2
5. High temperature 50^0C	21.1	38.0
6. Acidic solution	18.5	30.0
7. Sealed in oven	23.0	35.5

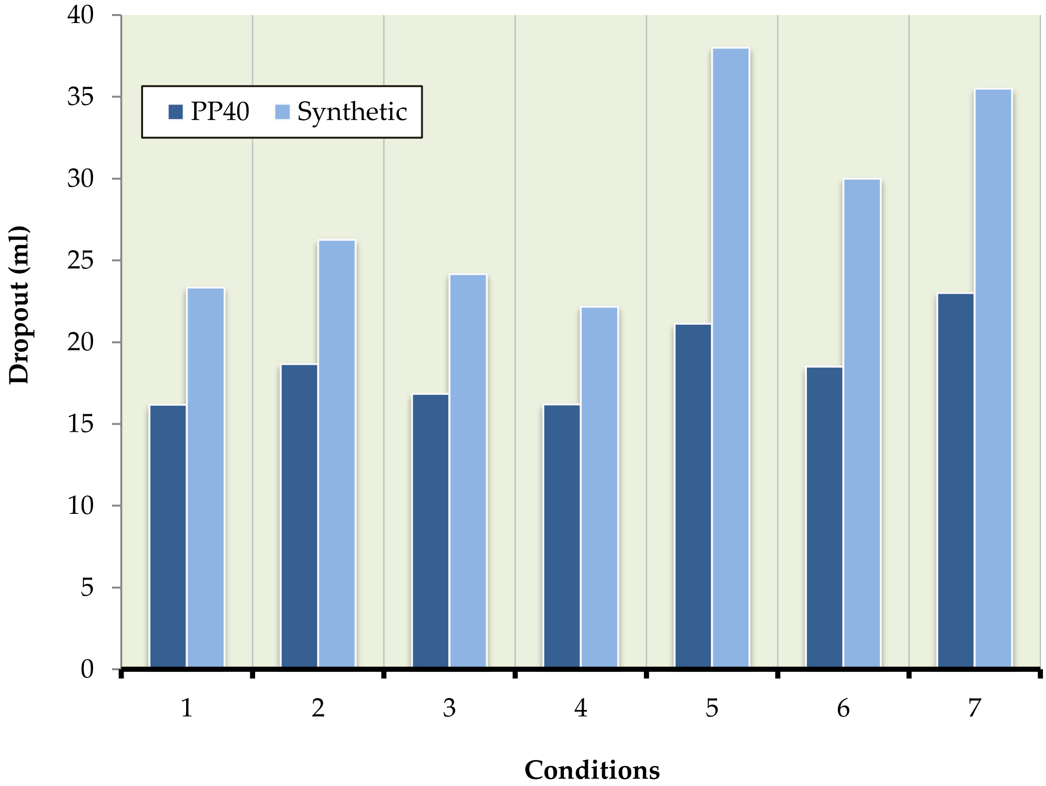


Figure 7.8: Dropout under different conditions for protein PP40 surfactant and synthetic surfactant

7.3.2. Set 1

In the instability tests carried out in Set 1, the constituent materials were generally the same with variation of the surfactants and with addition of calcium chloride and wetting agents to the mixes. The cement used in Set 1 was CEM I 42.5N. Table 7.3 shows the drop in level for protein surfactant and Table 7.4 show the drop in level for synthetic surfactant and surfactants TFAL-3 and Regular 3%. Variations in mixing methods were also included in Table 7.3. The readings from these tables; protein and synthetic surfactants were plotted in Figures 7.9 and 7.10. With both surfactants, the drop in level was lowest in the highest density concretes, 1400 kg/m^3 compared to those mixes at lower densities, 1000 kg/m^3 and 600kg/m^3. Comparatively, foamed concrete of 600 kg/m^3 densities were observed to have produced the highest drop in level across all w/c ratios. In high density concretes, the presence of sufficient fillers induced limited spaces and prevented the bubbles from expanding. The bubbles are 'confined' because the surface tension of the bubble is more than the internal pressure, hence preventing expansion and rupturing of the bubble. Compared to lower densities, this resulted in least drainage. In contrast, a small amount of fillers provided ample spaces which allowed the bubbles to expand. When the bubbles expanded and collapsed at a faster rate, the drop in level was higher. The drop in level for foamed concretes using surfactants type TFAL-3 and Regular -3% were in the same range as synthetic surfactant.

In addition, there was a possible link with yield stress of the foamed concretes. As explained in section 5.3.2, the yield stress increased with increase in density. This is opposite to drop in level, where the drop decreased with increase in density as shown in Figures 7.9 and 7.10. Within the same low density of 600 kg/m^3 in the protein surfactant, the drop was higher in concretes with high w/c ratio compared to those with low w/c ratio. With reference to the same possible relationship, yield stress decreased with increase in w/c ratio, which is proportionate to drop in level. This pattern was repeated for concretes with densities of 1000 kg/m^3 and 1400 kg/m^3.

Overall, the foamed concrete mixes using synthetic surfactant produced higher drop in level compared to mixes using protein surfactant. There was no clear pattern in the drop level with regard to change in w/c ratio. In addition to higher drop out in synthetic surfactant as mentioned in section 7.3.1, further studies were done using protein surfactant.

Table 7.3: Total drop in level for protein surfactant (500 mm cylinder height)

	Density (kg/m³)					
	600		**1000**		**1400**	
w/c ratio	a	b	a	b	a	b
0.4	53	15	20	55	0	0
0.5	90	65	30	80	0	0
0.6	150	124	37	70	10	10

Table 7.4: Total drop in level for synthetic; TFAL-3 and Regular -3% surfactants (500 mm cylinder height)

	Density (kg/m³)				
Surfactant	Synthetic			TFAL -3	Regular -3%
w/c ratio	**600**	**1000**	**1400**	**600**	**600**
0.4	200	105	0	190	200
0.5	185	55	0	180	170
0.6	105	55	10	100	110

Note:

1. Mixing condition:
   a. No waiting
   b. 30 minutes waiting after base mix

2. Colour : Drop in level (mm)

Colour	Drop in level (mm)
	>201
	151 – 200
	101 – 150
	51 – 100
	11 – 50
	< 10

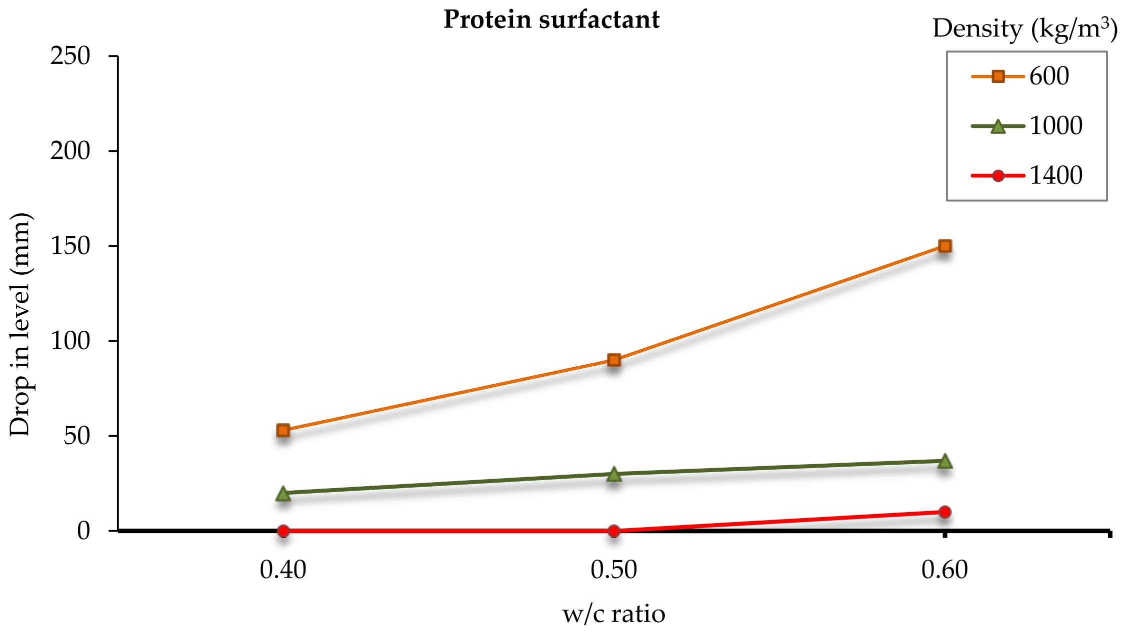


Figure 7.9: Drop in level for foamed concrete mixes using protein surfactant in 500 mm cylinder

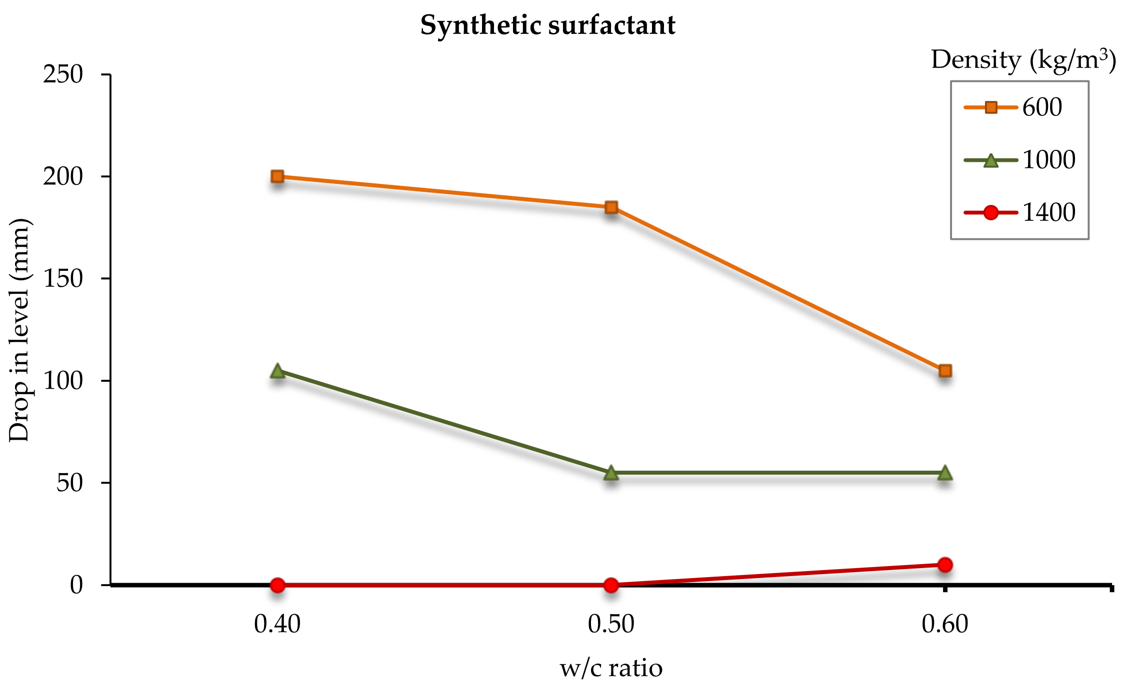


Figure 7.10: Drop in level for foamed concrete mixes using synthetic surfactant in 500 mm cylinder

In this experiment, a variation in mixing method was adopted to study the effect on the drop level. Figure 7.11 shows a variation in mixing method using a protein surfactant. In mixing condition B, the base mix was left for 30 minutes before including the foam. The hypothesis was to investigate whether the resultant mix was more stable and, thus, leading to less drop in level. As shown in Figure 7.11, in all three densities, there was no obvious trend evident between the two parameters of mixing method and drop in level. In density 600 kg/m^3, mixing condition B resulted in a drop in level. In density 1000 kg/m^3, mixing condition B increased this drop further whilst no change in level was observed with the density 1400 kg/m^3 density concretes across the two mixing methods. After 30 minutes, the base mix became highly alkaline and also rich in divalent (Ca) ions. Additionally, within this 30 minute period, the base mix precipitated, which would help stabilise the bubbles. The precise way in which the delay in adding the foam had any effect on the stability was not fully understood. This is a point for potential further investigation, in particular, by looking into the chemistry of the foamed concretes with relation to effect of pH values, surfactant concentrations and precipitations to the bubble walls and stability.

In another variation using protein surfactant, calcium chloride ($CaCl_2$) was added to the mix at 2% and 4% of cement content. Calcium chloride was known to be the most common accelerator for typical concretes over many decades, although its use had serious effects in promoting corrosion of the steel reinforcement. In the current study, calcium chloride was included to investigate the theoretical approach regarding how accelerated setting times may stabilise and reduce drop in level. The additional Ca^{2+} ions added to the calcium from the cement accelerate reactions. The results in Figure 7.12 show a reduction in dropped level when 2% was added and a further reduction that resulted when using 4% $CaCl_2$. This is expected because calcium chloride accelerated the setting times.

In a further experiment to investigate the relationship between smaller bubbles and instability, a wetting agent was added to the foamed concrete mixes. As explained in Chapter 6, the addition of a wetting agent reduced the bubbles' sizes (Figures 6.21 to 6.25). Figure 7.13 compared the microstructure of foamed concrete density 600 kg/m^3 without any wetting agent with using 1% wetting agent. Since smaller bubbles drain at a slower rate compared to bigger bubbles, theoretically, this may result in more stable mixes. As shown in Figure 7.14, the addition of wetting agent produced a reduction in the drop level in all the foamed concrete mixes. The drop was most significant in the mix of density 600 kg/m^3 where two different percentages of wetting agents were examined. When 1% of wetting agent was added, the drop in level improved remarkably (Figure 7.14). This occurred across the three w/c ratios which were investigated. The drop in level did not improve further when 2% of wetting agent was incorporated in the density 600 kg/m^3 mix (Figure 7.14). However, it was noted that, although the drop in level improved when wetting agents were added, the foamed concrete specimens were brittle when demoulded after 24 hours (Figures 7.15 and 7.16). Similar improvement was observed in the drop level for density 1000 kg/m^3, even though the improvement was not significant.

Rapid hardening Portland Cement (RHPC) was investigated and replaced CEM I 42.5N cement 100%. The drop in levels for foamed concrete mixes using 100% RHPC were less compared to foamed concrete mixes using CEM I (Figure 7.17). This reduction was observed in RHPC foamed concrete mixes at both w/c ratios. Conversely, when 1% of wetting agent was used, the drop in level for RHPC was greater compared to foamed concrete mixes using CEM I 42.5N. Whilst RHPC may have improved the setting times, the addition of wetting agents may have interfered chemically.

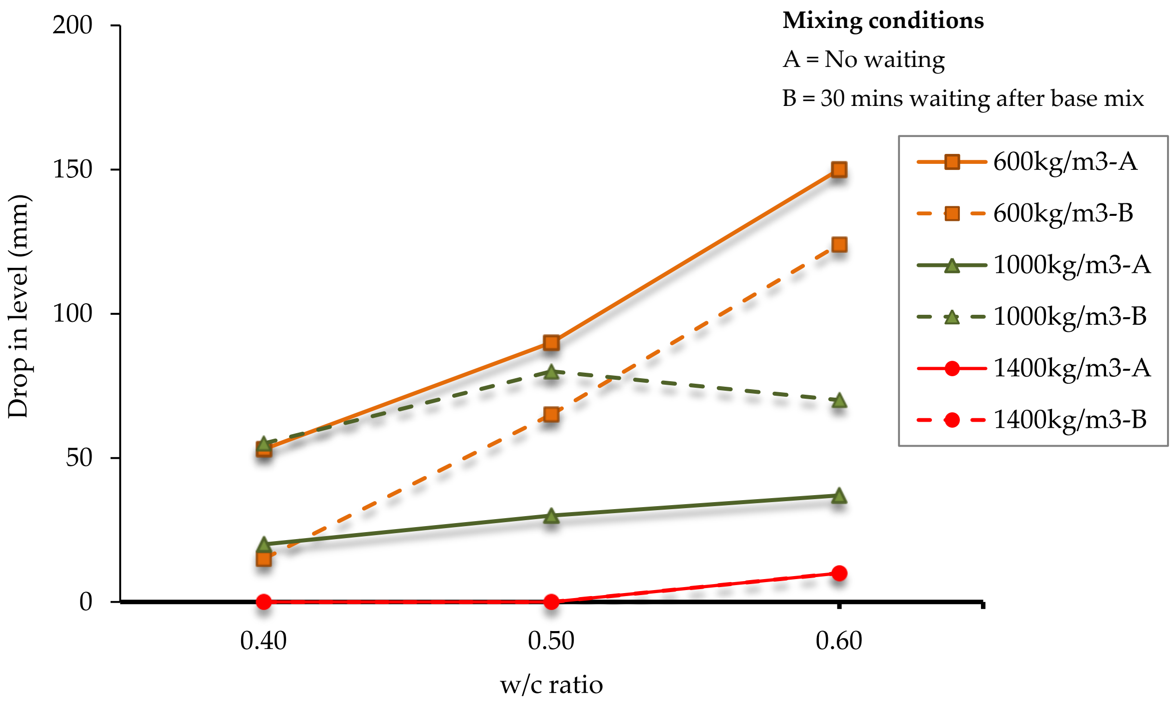


Figure 7.11: Drop in level for different mix methods in 500 mm height cylinder

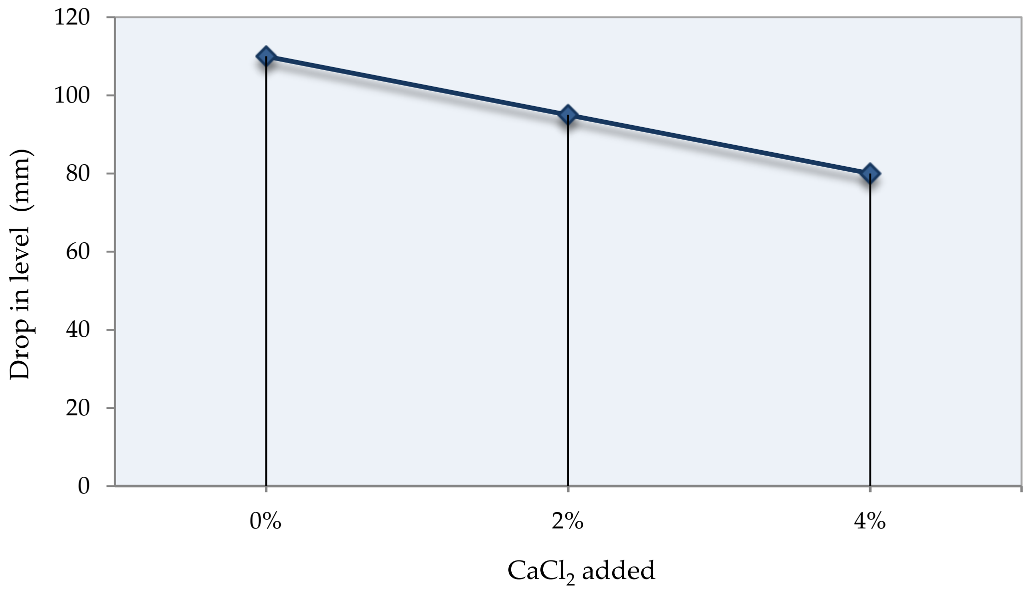


Figure 7.12: Drop in level with calcium chloride, $CaCl_2$, addition, % by weight of cement in 500 mm cylinder height

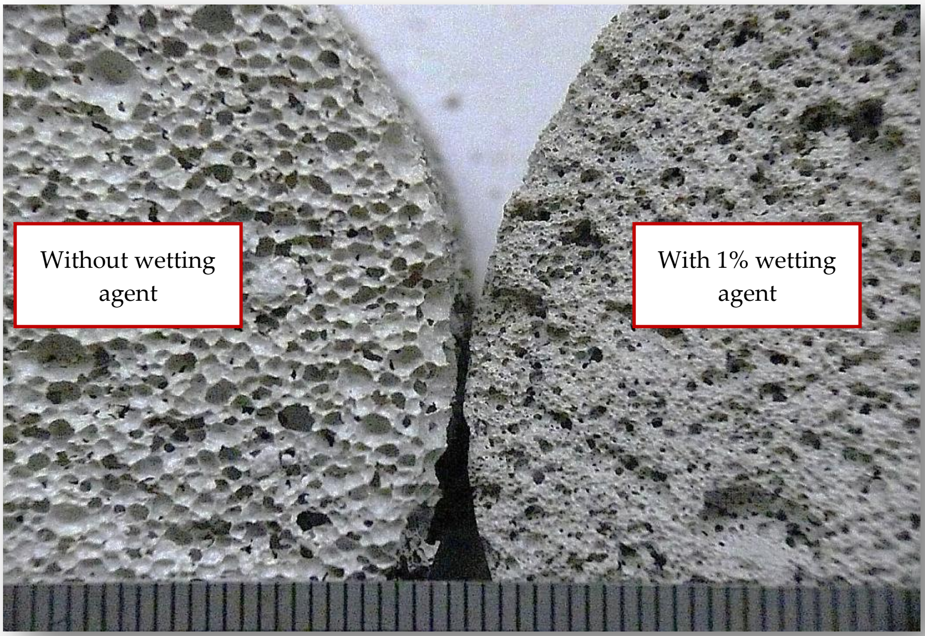


Figure 7.13: Comparing foamed concrete specimens, density 600 kg/m³ with and without wetting agents

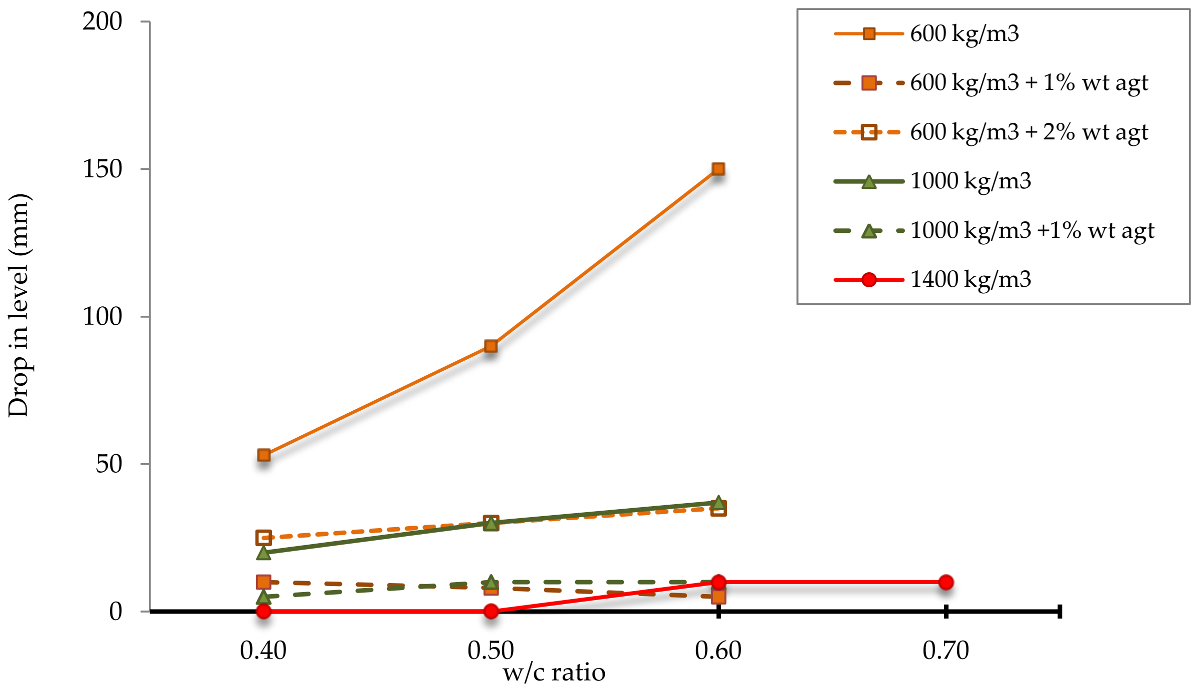


Figure 7.14: Drop in level with addition of wetting agents in 500 mm height cylinder

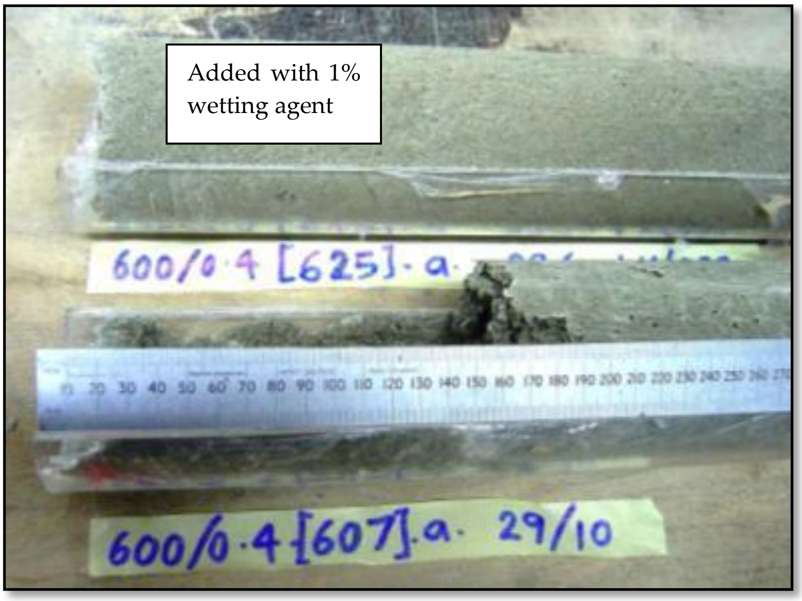


Figure 7.15: Foamed concrete 600 kg/m³ density with 1% wetting agent and without wetting agent

Figure 7.16: Foamed concrete 600 kg/m³ density with 1% wetting agent

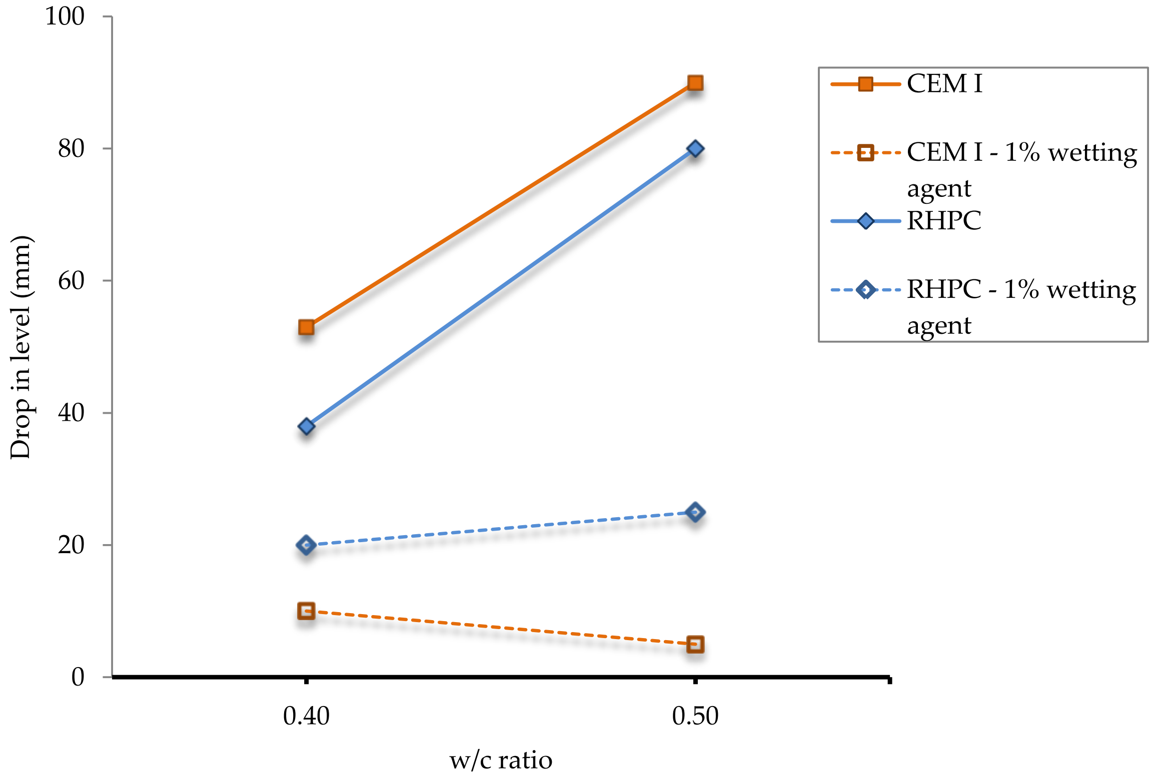


Figure 7.17: Drop in level using different cement types and with the addition of wetting agents for 500 mm height cylinder

7.3.3. Set 2

In Set 2, different constituent materials were used to assess the effect of differing fineness and variation in the proportions of particles on instability. In the first study in Set 2, different cement types were employed. When 30% of the CEM I 42.5N was replaced with fine fly ash, (FA_f) the total cementitious materials were finer compared to the mixes that used CEM I 42.5N only. This is because fly ash was much finer compared to CEM I 42.5N. The fineness of the cements was increased further using 20% metakaolin in replacement of CEM I 42.5N; this produced no drop in level. This part of the study sought to investigate the hypothesis concerning cement fineness and instability, namely, finer cements reduced the drop in level; thus increased in stability.

As shown in Figure 7.17, the percentage drop in the initial concrete decreased as cement fineness increased. Thus, this current research supported the hypothesis that increased in cement fineness improved stability. In this theory, the fineness of the cement plays a significant part in protecting the bubbles. The presence of high fineness cement particles 'stabilises' the bubbles by distributing bubbles into smaller sizes and protecting the bubbles from coalescing.

In a further study, fillers of different fineness were examined. Fifty per cent of sand was replaced with coarse fly ash (FA_c). The percentage drop in level was reduced compared to concretes with sand only (Figure 7.18). When 100% sand was replaced with FA_c, the percentage drop in level increased further. This phenomenon can be explained by the effect of finer pores on instability, akin to the effect of cement fineness. When the fillers were coarse for example, as with sand, the bubbles clustered and formed irregular pores that were large and irregular. When finer fillers were employed, there was a better distribution of bubbles, disallowing the bubbles to expand, which resulted in more stable mixes.

As part of the objective of studying the effects of other parameters, various cylinder heights were used for two foamed concrete mixes of different densities of 300 kg/m^3 and 600 kg/m^3 at w/c ratio 0.50. In all cylinder heights, the lower density, 300 kg/m^3 had a higher percentage drop in level compared to foamed concrete mix of 600 kg/m^3 density. Higher cylinder heights produced a higher percentage drop in level in both densities (Figure 7.19).

Several theories have emerged regarding the high percentage drop in density 300 kg/m^3. In low density concretes, the percentages of solids were lower compared to the percentage of foam, which allowed the bubbles to expand. In contrast, higher density concretes had more filler which confined the bubbles from expanding. The high foam percentage allowed the bubbles to coalesce easily. The bubbles adjoined each other, amalgamated and formed bigger bubbles. When more bubbles grew at the expense of smaller bubbles, the bubbles ruptured as they exceeded the 'critical wall' thickness. This resulted in more drainage compared to higher densities.

The cause for higher percentage drop in tall cylinders can be multifactorial, namely, increased pressure due to height, amount of foam and its effect on stiffening and drainage times. The pressure exerted by a static fluid depends on the depth of the fluid, since density and acceleration due to gravity are constant. In the cylinder, the pressure at any particular depth depends on the height of the mix above that point; thus, taller cylinders induced more pressure. The amount of foam incorporated into the mix has an effect on stiffening time of foamed concrete. Lower density, means a higher percentage of foam and has longer stiffening time (since foaming agents have retarding properties). During the hydration process, the foam bubbles were initially 'active'; the gravitational force caused the fluid to drain downwards and the bubbles to move upwards. Subsequently, the liquid phase progressed to 'gelling up' phase which resulted in the slow-moving bubbles. Eventually the 'gelling up' phase shifted to the solid phase where the whole matrix hardened. Hypothetically, when the stiffening time was delayed, the progression continued longer which resulted in more drainage.

7.3.4. Set 3

In Set 3, low density 300 kg/m^3 concrete was investigated with two blends of cement mixes; and for a single 0.50 w/c ratio. The first blend was 52.5 grade Portland Cement (CEM I 52.5R) with Calcium Sulfoaluminate (CSA) and the second blend was CSA and fine fly ash (FA_f). All combination ratios of CEM I 52.5R and CSA produced between 0-5 percent drop in level, an indication of stable mixes (Figure 7.20). Unlike the previous studies Sets 1 and 2, which used grade 42.5N Portland Cement, in this study, CEM I 52.5R was employed. CEM I 52.5R is a rapid setting type cement. The objective was to accelerate the hardening times before the bubbles started to rupture rapidly as investigated previously, in section 7.3.2, using rapid hardening Portland cement (RHPC) and mixes which included calcium chloride. Additionally, CSA cements were employed because of their expansive properties. When CSA cements hydrates, large ettringite needles were formed, thus filling up the spaces. The blend of CEM I 52.5R and CSA resulted in stable mixes.

In the second blend of CSA and fine fly ash, FA_f, variations in proportions and w/c ratios were examined in relation to the rheological properties of the mixes. The objective was to study the effect of CSA replacement with FA_f, at different proportions. All the mixes were stable, with drop in level of less than 5% (Table 7.5). From this observation it was found that CSA was effective in sustaining stability even when replaced with FA_f at different proportions and w/c ratios.

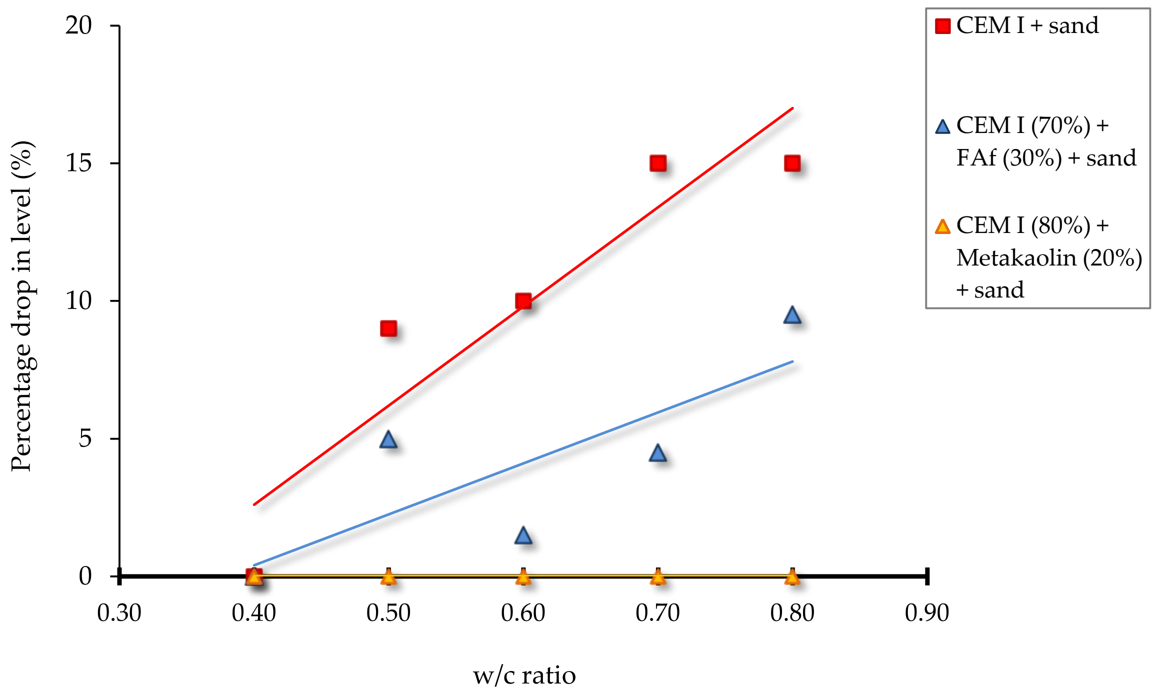


Figure 7.18: Percentage drop in level with varying cement fineness

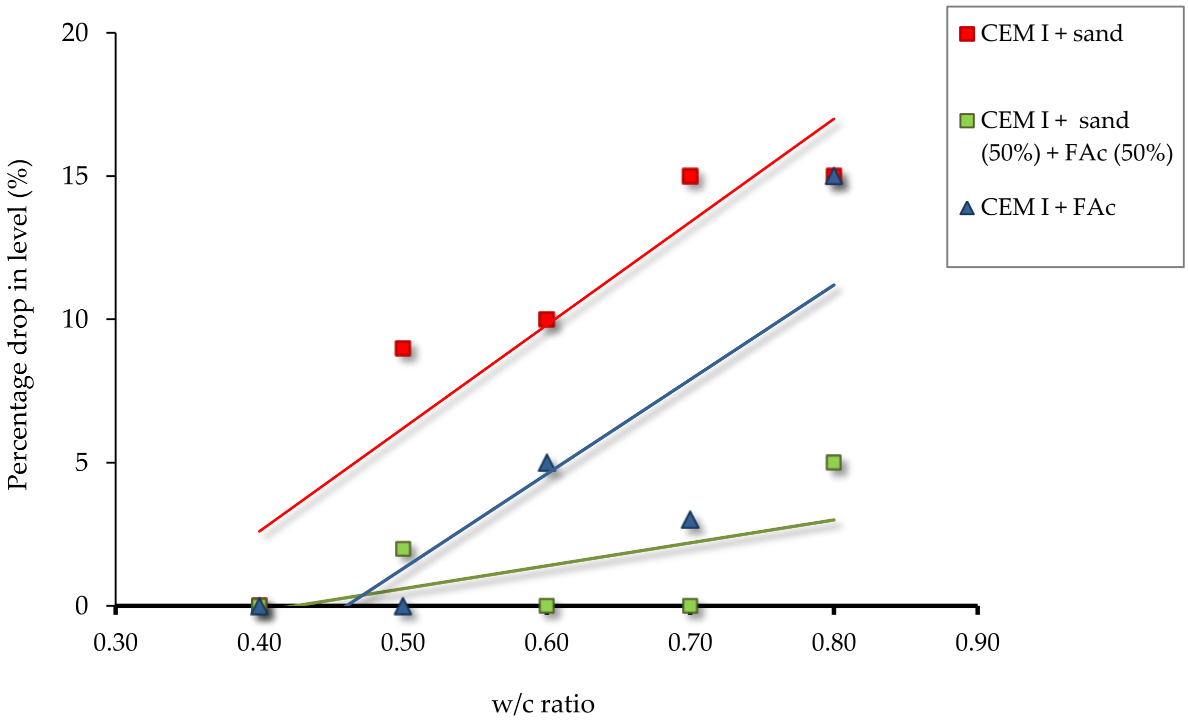


Figure 7.19: Percentage drop in level with varying filler fineness

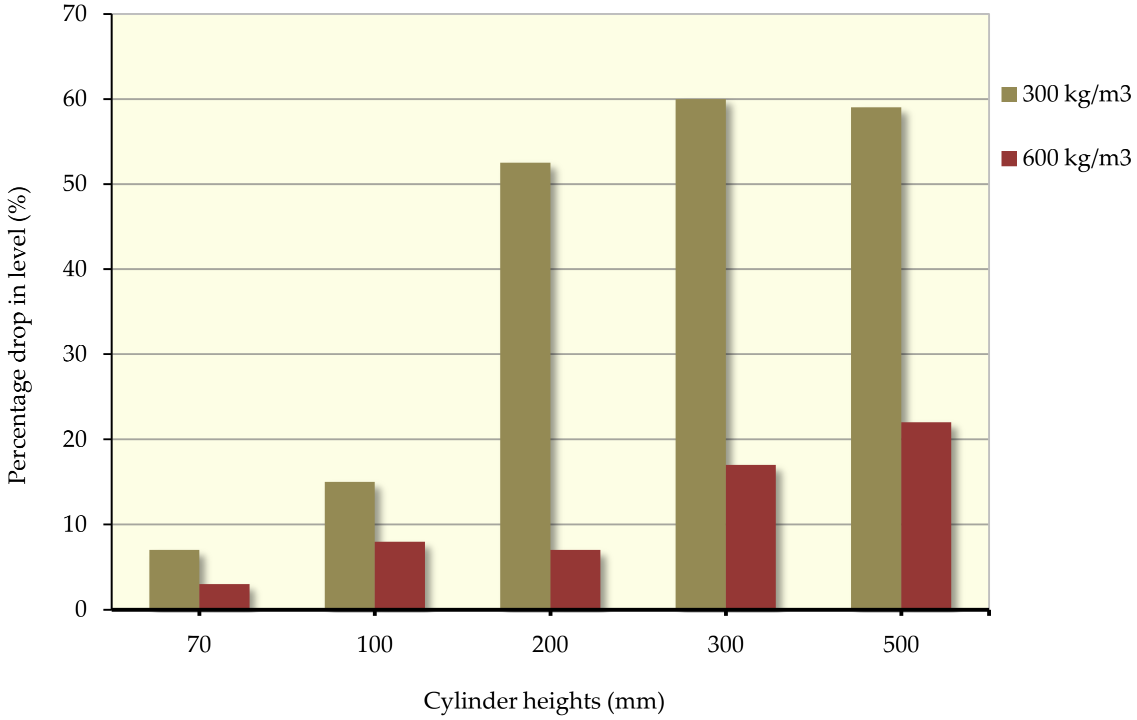


Figure 7.20: Percentage drop for various cylinder heights

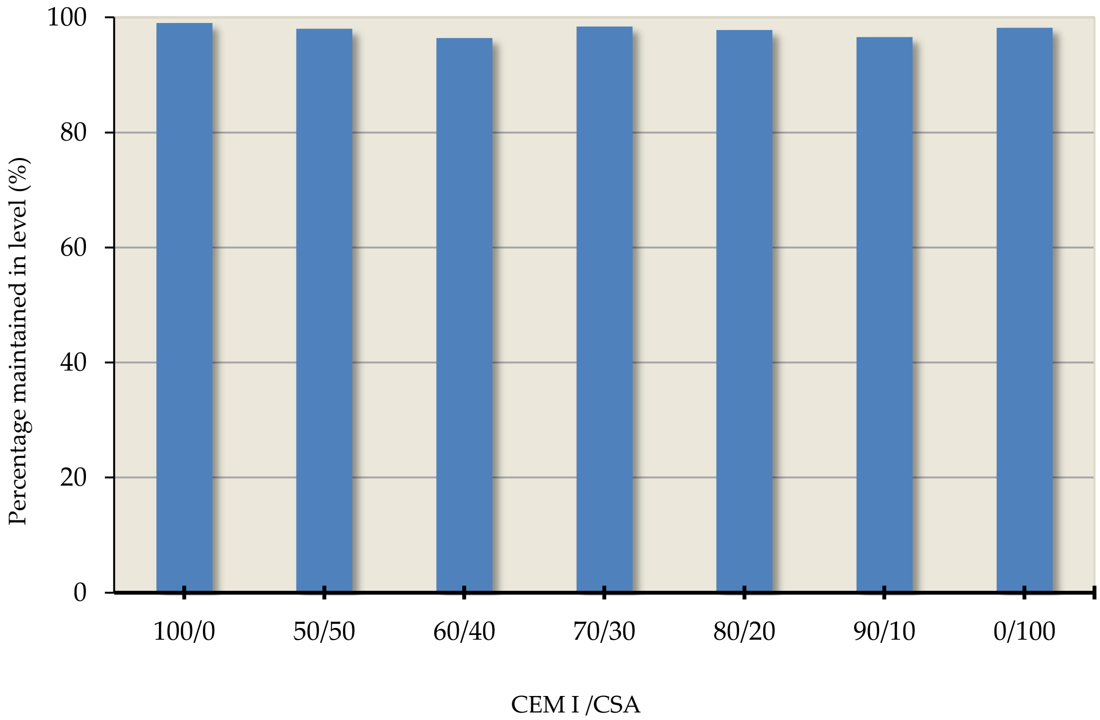


Figure 7.21: Percentage maintained in level for CEM I 52.5R/CSA blend

Table 7.5: Stability results in blends of CSA and FA_f

CSA : FA_f	w/c ratio	Measured plastic density (kg/m^3)	Stability (< 5% drop in level)
40/60	0.45	315	Stable
50/50	0.45	310	Stable
60/40	0.45	312	Stable
40/60	0.5	271	Stable
50/50	0.5	335	Stable
60/40	0.5	301	Stable
40/60	0.6	322	Stable
50/50	0.6	285	Stable
60/40	0.6	287	Stable
40/60	0.65	280	Stable
50/50	0.65	292	Stable
60/40	0.65	315	Stable

7.4 SUMMARY OF RESULTS

The aim of the current study was to investigate the effects of a range of parameters which included densities, w/c ratios and variations of materials to find the causes of instability in foamed concrete. The empirical results reveal a multitude of possible defined factors affecting the instability of foamed concrete mixes. These results are linked to other studies; rheological properties and the microstructure of the foamed concrete and the relationship will be discussed further in Chapter 8: Analysis and Discussion.

There were four sets of tests; dropout tests, Set 1, Set 2 and Set 3. The main Portland Cement used in Set 1 and 2 was grade CEM I 42.5N whilst Set 3 used grade CEM I 52.5R.

1. Dropout tests

In the dropout tests, the drainage from neat bubbles was measured. In neat bubbles, coarsening and draining cause coalescence, which leads to collapse of the bubbles. However, it is not clear whether there exists a similar pattern in the characteristics of the neat foam bubbles and the bubbles formed in the foamed concrete. The variations in this section of the study included two different types of surfactants and different mixing and draining conditions. For these tests, the significant outcomes were:

a. The dropout from protein surfactants produced less dropout compared to synthetic surfactants, which was an indication of stronger bubbles.

b. The external temperature and relative humidity played a role in bubbles collapsing. High temperature induced bubbles to collapse at a faster rate. The use of deionised water decelerated bubble collapse as indicated by least drainage.

2. Set 1

Using the same basic constituent materials, the variations in Set 1 included variation in the surfactants, densities and w/c ratios, the addition of wetting agent, calcium chloride, slight differences in mixing method and replacement of CEM I 42.5N with RHPC. The significant outcomes arose from this set were:

a. Foamed concrete mixes from synthetic surfactants had higher drop in level compared to foamed concrete mixes from protein surfactant.

b. The higher densities; 1000 kg/m^3 and 1400 kg/m^3 were more stable compared to lower density, 600 kg/m^3. In 600 kg/m^3, the drop was highest at w/c ratios 0.40.

c. There was no obvious pattern in the drop, when another variation of mixing method was adopted (30 minutes delay in adding preformed foam).

d. The addition of $CaCl_2$ and wetting agents improved the drop in level; although the latter produced a 'weaker' foamed concrete.

e. Rapid hardening Portland Cement (RHPC) improved the drop in level but not with inclusion of a wetting agent.

3. Set 2

In Set 2, the main variations were the differing cementitious which was achieved by replacing percentages of the main CEM I 42.5N with other cement types; FA_f and metakaolin. Similarly, the fineness of the fillers was also varied by replacing sand with FA_c at different percentages. From this part of the investigation, the significant results were:

a. The drop in level improved when the fineness of cementitious materials increased.

b. The drop in level improved when the fineness of fillers increased.

c. Lower density, 300 kg/m^3 had a higher percentage drop compared to higher density, 600 kg/m^3.

d. Taller cylinders produced a bigger drop compared to shorter cylinders.

4. Set 3:

In Set 3, there were 2 parts of study using blended cements. The first was of blends of CSA cement with CEM I 52.5R at 0.50 w/c ratio at different percentages and the second was of blends of CSA with FA_f at varying w/c ratios (0.45 to 0.65) and three different percentage blends. The significant outcome from this study was:

a. Cement blends of CEM I 52.5R and CSA produced stable foamed concrete at varying proportions which resulted in small drop (less than 5 percent).

b. Cement blends of CSA and FA_f at w/c ratios ranging between 0.45 to 0.65 at varying proportions resulted in a small drop (less than 5 percent), which dramatically improved stability at low density, 300 kg/m^3.

CHAPTER 8: ANALYSIS AND DISCUSSION

8.1 INTRODUCTION

This study comprised two phases: Phase 1 was intended to investigate the possibility of foamed concrete being used as a structural element while Phase 2 complemented the pilot study. The initial target of the study in Phase 1 was to confirm the status of foamed concrete as a structural material. The aim was to improve the serviceability limit and reduce deflection, which was achieved by post-tensioning. Glass-fibre reinforced polymer rod (GFRP) was used to post-tension the beams because of its compatibility with foamed concrete. However, the outcome of the first load test was not as expected and there was a high deflection on the first crack. This unanticipated occurrence was not related to the foamed concrete as a material, but it was identified as a problem with the reinforcement. Nevertheless, there was a positive outcome to this test in that initial readings indicated that foamed concrete was behaving in a predictable manner when it hogged and sagged with added stress by the tensioned bar. This action suggested that it is possible to produce post-tensioned foamed concrete with improved reinforcement. The minimum strength of 25 MPa, a criterion for foamed concrete to be accepted as structural material, was achievable with density 1500 kg/m^3 at 96 days using fly ash. No attempt was made to increase the density, as lightweight aggregate concrete would have provided a more suitable method for this to be achieved.

Following this episode, a different approach was taken to study the fundamental aspects of foamed concrete. The focus of the research was diverted to understanding the behaviour and characteristics. These objectives remain within the spectrum of exploring the potential of foamed concrete. This research was based upon the intriguing characteristics relating to the rheological properties of foamed concrete, the microstructure of the material and their effects on the stability, which served as the ultimate criterion. In view of the fact that the construction industry was moving towards using foamed concrete of lower densities, it was logical to complement movement within the industry on this use. Achieving densities lower than 600 kg/m^3 poses a technical challenge with regard to stability while maintaining flowability.

The studies encompassing Phase 2 were examination of the rheology, microstructure, and causes of instability in foamed concrete, which were presented in Chapters 5, 6 and 7 respectively.

This current chapter draws together the discussion of the results obtained in Phase 2 of the study.

There were some uncertainties regarding the behaviour of foamed concrete, hence hypothetical explanations were constructed from these experiments.

8.2 HYPOTHESES

Four hypotheses were developed in an attempt to explain the findings, although not all occurrences are supported by these hypotheses.

8.2.1 'Cannibalistic' theory (H1)

This theory accounts for the ease of the bubbles to coalesce due to the differences in the internal pressure. Initially, the bubbles 'arrange' themselves to be in a state of equilibrium. When the bubbles adjoin, they 'grab' each other, amalgamate and form bigger bubbles. In this argument, the size of larger bubbles grows at the expense of smaller bubbles (Figure 8.1)

8.2.2 'Confinement' theory (H2)

This theory formulates that, in a stable condition, there is adequate yield stress in a base mix which helps stabilise the bubble structures. This is caused by the presence of sufficient fillers that limit the spaces and prevent the bubbles from expanding. The bubbles are 'confined' because the surface tension of the bubble is greater than the internal pressure, hence preventing it from expanding and breaking the bubble. The finer cements and fillers distributed in the matrix confine the bubbles and prevent them from expanding. When the bubbles are confined, the process of expansion and rupture decelerates and increases the stability. In contrast, a small amount of the fillers provides ample spaces and this allows the bubbles to expand (Figure 8.2)

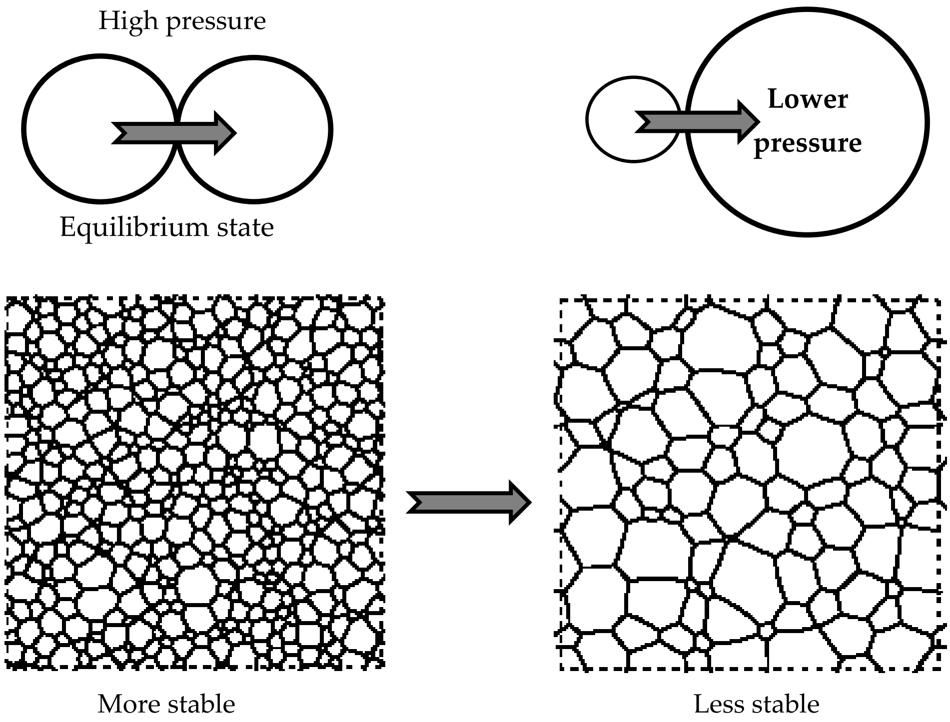
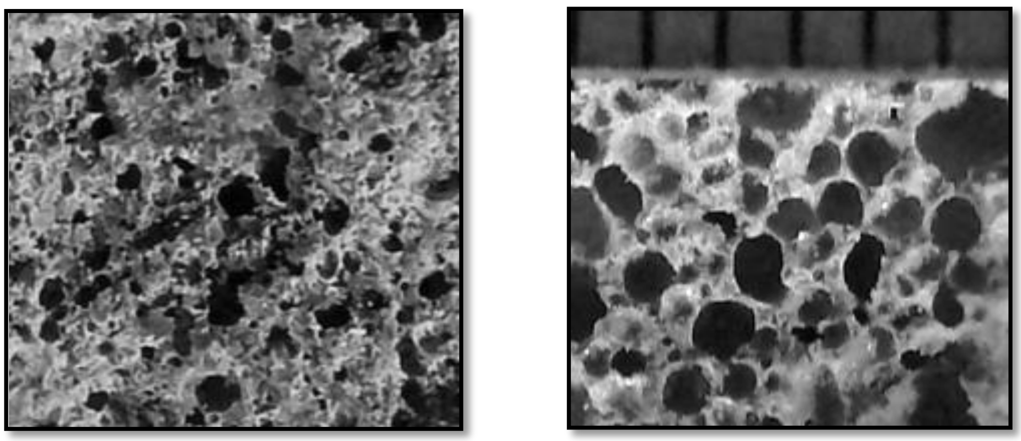


Figure 8.1: Schematic diagram for ‘Cannibalistic’ theory



Density 1400 kg/m³

- Confined bubbles prevents expansion and increases stability

Density 600 kg/m³

- Small amount of fillers allows bubbles to expand

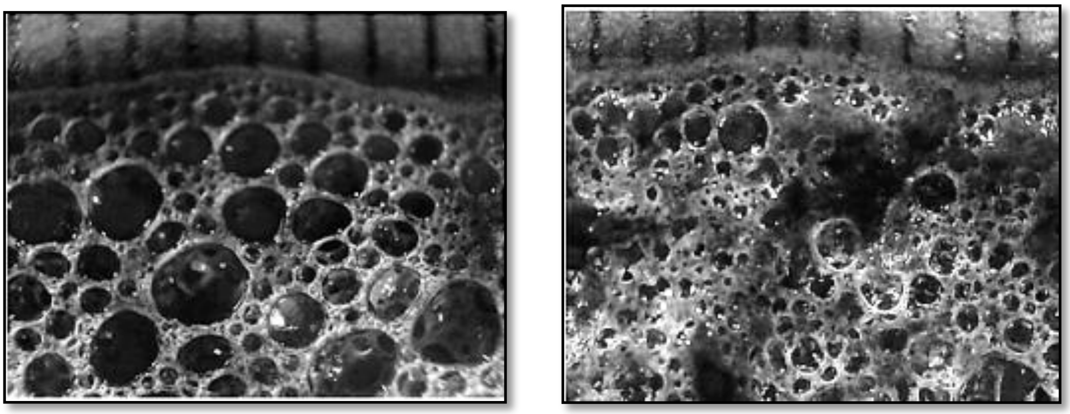
Figure 8.2: Schematic diagram of ‘Confinement’ theory

8.2.3 'Cement fineness' theory (H3)

In this theory, the fineness of the cement plays a significant part in protecting the bubbles. The presence of high fineness cement particles 'stabilises' the bubbles by distributing bubbles into smaller sizes and protecting the bubbles from coalescing (Figure 8.3).

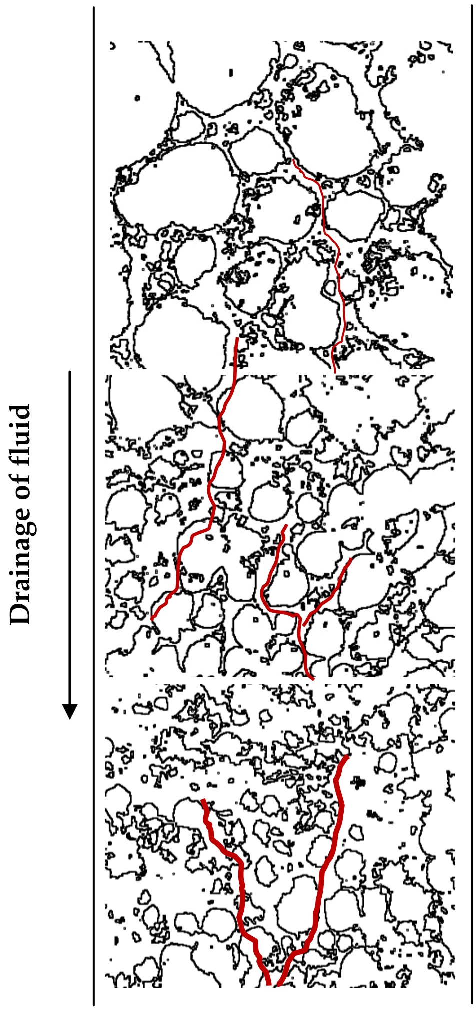
8.2.4 'Hardening' theory (H4)

The presence of cement and water induced the process of hydration. In the initial fluid phase, the bubbles are 'active'; the gravitational force causes the fluid to drain downwards and the bubbles to move upwards (Figure 8.4). While this is happening, the liquid phase progresses to a 'gelling up' phase which results in the bubbles becoming slow-moving. Eventually the 'gelling up' phase shifts to the solid phase, where the whole matrix hardens. At this juncture, the bubble sizes and positions become fixed. Ideally, the bubbles must have a reasonably long lifetime to withstand the processes and rupture caused by coalescence of the adjacent bubbles and due to the surface tension gradient in the vertical direction resulting from the liquid drainage.



Attraction of cement particles 'stabilised' the bubbles and prevented the bubbles from coalescing

Figure 8.3: Schematic of 'Cement fineness' theory



Drainage causes the liquid to drain downwards and the bubbles to move upwards.

The bubbles were active in the initial fluid state, then began to progress into the 'gelling up' and became slow moving. In the solid state, the bubbles sizes became fixed.

Figure 8.4 : Schematic diagram of 'Hardening' theory

8.3 SUMMARY OF FOAMED CONCRETE PROPERTIES

In order to establish the relationship between the properties, the individual sets of results are summarised in each section accordingly.

8.3.1 Rheology

The first research in this set of studies was the study of foamed concrete rheology. Predictions of the rheological behaviour of foamed concrete to different conditions and mix constituents were uncertain because foamed concrete is a mass of concentrated dispersions of solids in water. The rheological properties are controlled by the proximity of particles, the strength, shape and surface properties of the particles together with the composition of the water. Foamed concrete conforms to the Bingham model, which is defined by values of two rheological parameters: yield stress and plastic viscosity. Yield stress is the minimum stress required to initiate flow and plastic viscosity is the measure of the internal resistance for fluid to flow. In this experiment, a Brookfield viscometer (two point tests) was mainly used to obtain the yield stress and plastic viscosity values. The Dundee modified Marsh cone was also employed to study the flowability, albeit that this is a single point test. From this experiment, it was found that changing the densities exhibited significant variance in the rheological values. Altering the w/c ratio had a considerable variation in the rheological values. An increase in density induced an increase in yield stress. The high density corresponded to a high percentage of solids and a reduced percentage in the foam/air per volume, and made it harder to initiate flow. Lower w/c ratio at any one density induced a higher yield stress value compared to higher w/c ratio because having less water required a higher force to initiate flow.

Plastic viscosity increased when density increased, which implied that the internal resistance increases with higher densities. A further, less significant, effect was that plastic viscosity decreased with an increase in w/c ratio. Since the w/c ratio corresponds to the inter particle distance, an increase in water content reduced the internal resistance making it less viscous. In any one density, the mix with the highest w/c ratio showed the least plastic viscosity.

In a study of two densities, due to higher self-weight, the higher density gave a shorter flow time compared to the lower density. Other factors which affected the values were the mix constituents with different proportions and fineness. Cement fineness has an effect on the water demand which affects flowability, thus leading to a sticky consistence or non-flowability. When coarse fly ash replaced sand, the flow time reduced markedly, indicating that fineness of the fillers affected flowability.

In this study, yield stress values were found to be within the range of 1.19 N/m^2 to 30.50 N/m^2, the lowest value being foamed concrete with lowest density at highest w/c ratio. The measurable range in the modified Marsh cone values ranged from less than 1 second to approximately 3 minutes, with an acceptable value being within the range between 1 to 2 minutes. Corresponding to this flowable range, the yield stress was found to be between 6.0 and 8.5 N/m^2.

8.3.2 Microstructure

The second study focussed on observing the microstructure, which was expected to influence its characteristics. The motivation for the current research was to identify the governing factors which induced some phenomenon and their relationships with other properties. However, the characterisation was not easy because the microstructure was complex and heterogeneous. Improvements in microscopy techniques have provided new insights into the microstructure of foamed concrete, giving a better understanding of the material. Adopting the advances in imaging technology, coupled with user-friendly software ImageJ, digital analysis of the air void system was attempted, even though the values were not definitive. Where it was not possible due to the nature of the specimens, visual analysis was attainable.

Several observations were made with regard to this second study. The properties of the bubbles were governed by few parameters. The surfactant was the key factor in the types of bubbles generated. Bubbles produced from a protein surfactant were more defined, not connected and closed cell. In contrast, those produced using synthetic surfactants were more open, had 'holes in hole' and were undefined. Within the same surfactant type, the most significant finding was that density had the greatest effect on the bubbles sizes. An increase in density resulted in a decrease in bubble size and increased bubbles counts, which can be explained using hypothesis H2. The amount of solids emerged as the deciding factor for the bubbles to expand. Increase in density relates to an increase in solids which minimises the spaces into which the bubbles can expand or amalgamate. More solids in the matrix constricted the expansion of the bubbles, maintaining the small bubble sizes until the whole matrix sets. This phenomenon was found to be similar in all mix proportions and constituents. In contrast, increase in the w/c ratio induced an increase in bubble sizes and decrease in bubble count. This condition can be explained using hypothesis H1, with regard to the solids in the mixture. High w/c ratio corresponded to an increase in inter-particle distance which created more space, hence the bubbles coalesce, amalgamate and form bigger bubbles. From this observation, the bubble diameters were found to be within the range of 0.1 to 0.5 mm. Bubbles larger than the range appeared more sporadically in lower densities and higher w/c ratios.

In the bubble size distribution, d50 less than 0.35 corresponded to stable mix with a drop in level of less than 5% in height which was achieved with densities of 1000 kg/m^3 and higher. This condition supports hypothesis H2. Foamed concrete mixes of 600 kg/m^3 experienced some occurrences of collapse. There were big bubbles; notably with d90 greater than 1 mm. The values of d50 in the stable mixes were not significantly smaller than the values of d50 in the mixes with a substantial drop in level. However, the values of d90 in the unstable mixes were noticeably larger than those of d90 in the stable mixes. Hypothetically, d90 was found to be source of instability for reasons not yet completely understood.

There are other significant findings from this observation. The addition of a wetting agent resulted in bubbles which disintegrated and thus caused the foamed concrete to become crumbly in nature. At low density, the bubbles in the top part of the hardened specimens were noticeably bigger compared to the bubbles at the bottom part of the specimens. This phenomenon can be explained using hypothesis H4, the hardening theory. Aside from the quantifiable factors, time was an essential aspect which influenced the microstructure. With time, bubbles expanded due to the differences in internal and external pressure and eventually ruptured as the walls became too thin. Ideally, the shorter phase of hardening time limited the process of expansion.

With regard to rheology, the bubble size was smaller with higher yield stress. In summary, bubble size was found to be a function of yield stress, plastic viscosity, material fineness and surfactant types.

8.3.3 Instability

The results from the experiments on rheology and microstructure contribute to the findings on foamed concrete instability, which is the subject of the next study. In this study, instability was assessed by observing the drop in level of the foamed concrete surface. Instability was found to be affected by a variety of factors.

In the initial dropout tests, temperature was the most significant factor, where the highest dropout was found under higher temperature conditions. Increase in temperature reduced the surface tension of bubbles and encouraged collapse. In contrast, the least dropout resulted from the use of deionised water, particularly because the impurities were removed. However, there was no evidence to correlate the characteristics of the neat foam bubbles to the bubbles formed in the foamed concrete. It was obvious that a protein surfactant produced less dropout than a synthetic surfactant, the justification for which is stronger, more stable and smaller bubbles with closed cell structure compared to those of synthetic surfactants.

In a variation of densities and w/c ratios, within a set of constituent materials, stability increased with an increase in density, which can be explained using hypothesis H2. The high percentage of solids in high density limited space and restricted the bubbles from expanding, which resulted in slower rupture. In contrast, a small amount of the fillers provided ample spaces to allow the bubbles to expand and coalesce easily. When the bubbles adjoined, amalgamated and formed bigger bubbles, larger bubbles grew at the expense of smaller bubbles, which supported hypothesis H1.

The variation of drop in level was not significant when the w/c ratio changed within the selected range. Within the same set, slight variation of mixing method did not improve the drop in level. However, when calcium chloride was added to the cement, the drop in level improved slightly, but the foamed concrete was more brittle. Similarly, slight improvement in the drop in level was observed with the use of Rapid Hardening Portland cement, an indication of the effect of hardening times. When the fineness of the constituent materials was increased, the drop in level decreased; indicating an improvement in stability. These phenomena can be explained by hypothesis H3. However, the use of metakaolin improved stability, but the mix suffered flowability issues because the surface area was too high and produced a sticky mix in lower w/c ratio.

In tall cylinders, higher percentage drop was linked to the exerted pressure which increased with depth. The gravitational force caused the fluid to drain downwards and the bubbles to move upwards which is greater in tall cylinders compared to short cylinders. The progression led from liquid phase to 'soft solid' phase and eventually to solid phase where the whole matrix hardened. This supports hypothesis H4.

In an entirely new set, cement types CEM I 52.5R cement and CSA dramatically improved stability. The blends of CEM I 52.5R, a rapid setting type cement and CSA cements produced stable mixes since they have expansive properties. The blends included replacement with percentages of FA_f; sustained stability even at low density, 300 kg/m^3. This added further weight to hypothesis H4. This discovery demonstrated that hardening time is a dominant factor.

8.4 RELATIONSHIP BETWEEN RHEOLOGICAL PROPERTIES AND MICROSTRUCTURE

This study shows that the bubble sizes are related to the rheological properties of foamed concrete. When the bubble sizes are tabled against yield stress and plastic viscosity, the existence of a relationship between these values is observed (Table 8.1). This empirical data was obtained from the same constituent materials, hence omitting other possible factors such as effect of fineness and hardening time. It is most striking that, in general, the bubble sizes reduced when the yield stress increased, as shown in Figure 8.5. The yield stress values, which corresponded to an acceptable flowability between 1 to 2 minutes, lie between 6.0 N/m^2 to 8.5 N/m^2. The corresponding bubble sizes are between 0.33 to 0.35 mm in diameter. Increase in yield stress and plastic viscosity reduced the bubble sizes although the effect of yield stress is more significant (Figure 8.6). Within the same density, the lower w/c ratio corresponded to smaller bubble sizes compared to higher w/c ratio.

8.5 RELATIONSHIP BETWEEN INSTABILITY AND MICROSTRUCTURE

The bubble sizes also corresponded to instability in foamed concrete. The increase in drop in level indicated an increase in instability that corresponded to larger bubble diameters. As previously noted, increase in density improved the stability in foamed concrete; hence the drop in level is less in higher densities. Correspondingly, the bubble sizes reduced with increased density. This relationship was found when using CEM I 42.5N, which was widely used in the current series of studies. The use of CEM I 52.5R and CSA cement, dramatically improved stability even at lower density 300 kg/m^3.

Table 8.1: Relationship between bubble sizes and rheological properties

	DENSITY								
	600 kg/m³			1000 kg/m³			1400 kg/m³		
w/c ratio	Yield stress (N/m^2)	Plastic viscosity (Ns/m^2)	Bubble diameter (mm)	Yield stress (N/m^2)	Plastic viscosity (Ns/m^2)	Bubble diameter (mm)	Yield stress (N/m^2)	Plastic viscosity (Ns/m^2)	Bubble diameter (mm)
0.4	7.6	0.11	0.41	16.8	0.66	0.23	52.8	1.18	0.16
0.5	3.7	0.09	0.43	11.0	0.33	0.28	43.6	1.07	0.18
0.6	01.8	0.08	0.47	2.6	0.29	0.33	21.8	0.85	0.21

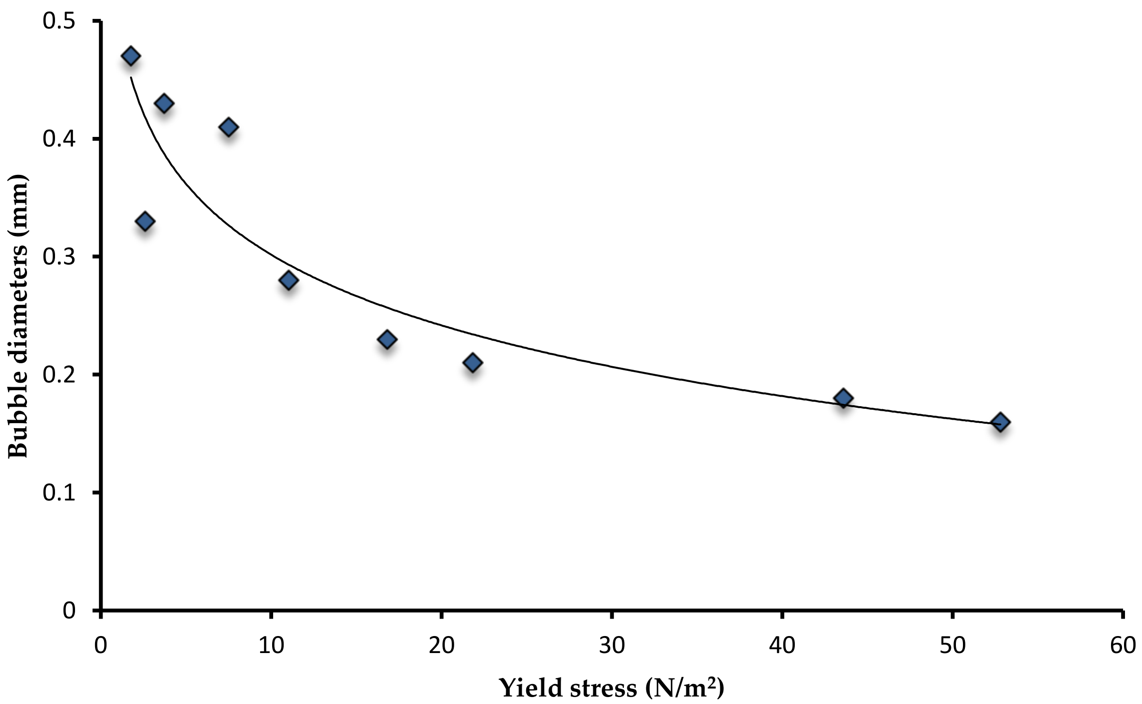


Figure 8.5: Bubble sizes against yield stress

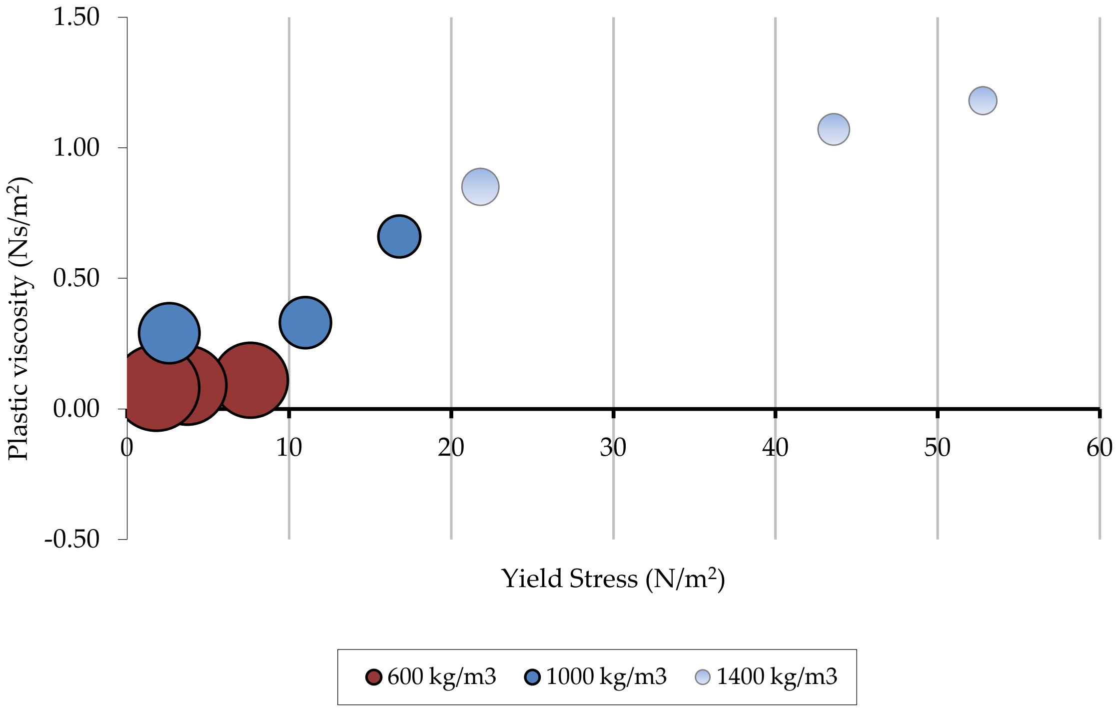


Figure 8.6: Schematic bubble sizes for varying yield stress and plastic viscosity

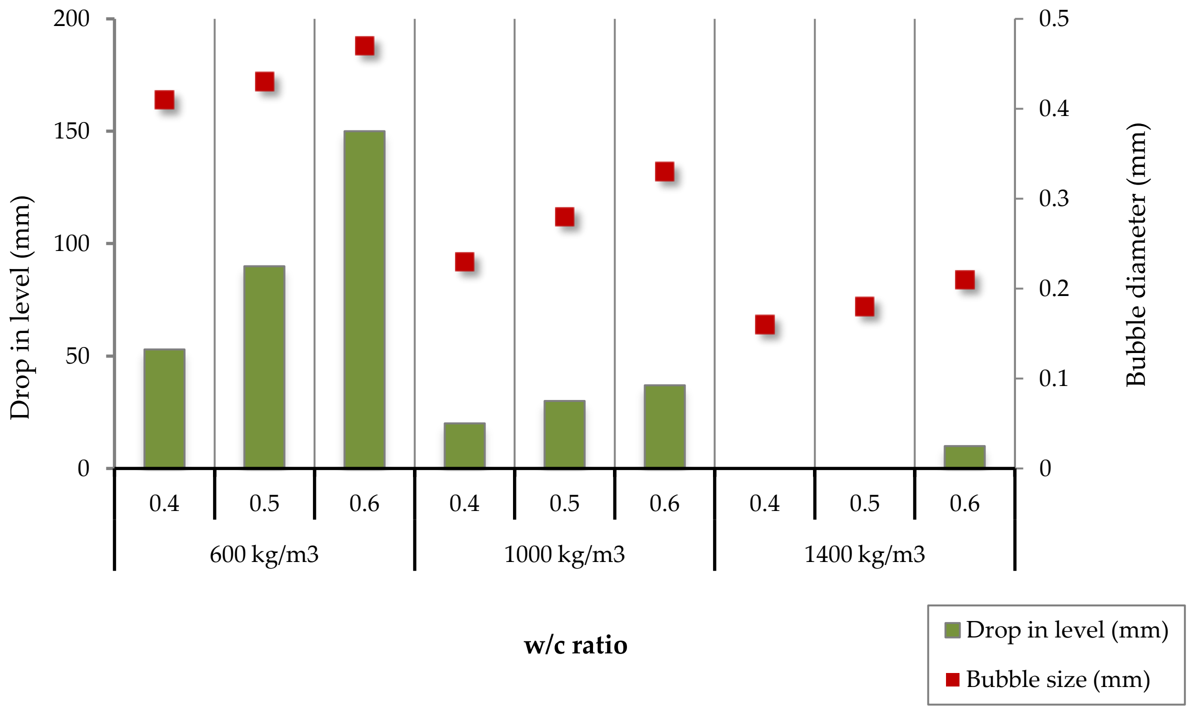


Figure 8.7: Relationship between instability and bubble sizes

8.6 CONCEPTUAL DEVELOPMENT TIMELINE

From these relationships, using stability of the foamed concrete as the ultimate criterion, it is possible to predict the stability of the foamed concrete by controlling the rheological properties and hardening time.

Foamed concrete mixes exhibit yield stress because the network of attractive particle interactions allows the suspension to support finite amount of stress without flowing. With time, rheological effect took place, where the bubbles coalesced, expanded and amalgamated (B1), as shown conceptually in the development timeline diagram (Figure 8.8). The progression induced bigger bubbles with thinner bubble walls which were no longer aqueous but have mixed with cement particles. This effect is multiplied by liquid drainage which resulted from the surface tension differences. With 'improved' condition, the pattern B2 is attainable by employing selected constituent materials and mix proportions.

The complex hydration of cement is continuous, where the rate changes with time. Increased time produced continual processes of bubbles expanding. With reduced hardening time, they are reduced and the rheological effect is minimised. This condition was achieved using CSA and CEM I 52.5R where the hardening time was shortened drastically (B3).

The bubbles typically have a limited lifetime where the strength decreased rapidly (shown as S1). With 'improved' intrinsic characteristics, smaller initial size, strong walls and sustainable strength, S2 is the ideal pattern of decreasing strength bubbles which allows the bubble to support its own weight for a longer duration until the whole matrix hardens. Inappropriate techniques of mixing and placing before setting may affect the air-void system and interfere with the stability of air-void system.

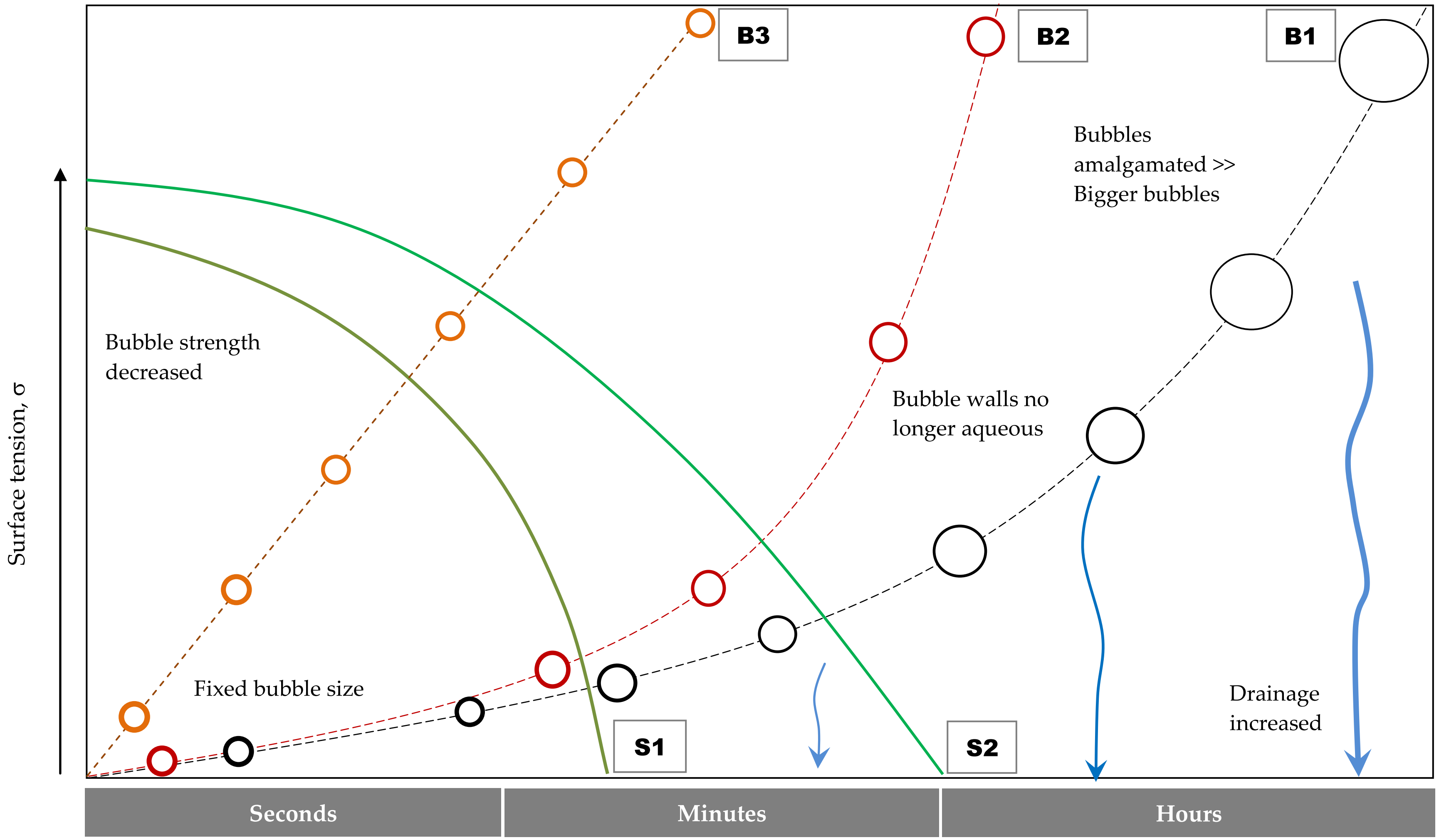


Figure 8.8: Conceptual development timeline

CHAPTER 9: CONCLUSION

9.1 OVERALL CONCLUSION

An improved understanding of the influence of constituent materials and mix proportions on the basic properties and characteristics of foamed concrete is needed. This study looked at a selection of parameters which may affect the design of foamed concrete. One of the important properties is the rheological properties which are accepted as having direct relation to the behaviour and properties of all cementitious materials. Since the importance of the rheological properties has been acknowledged in the literature and in practice, this research was done to investigate the effect of constituent materials and the mix proportion on the rheological properties of foamed concrete. Another important area that required further research was the understanding of bubble structures which were known to vary with different mix proportions and constituent materials. In this study, a few parameters were selected and their relationship to the microstructure was observed. Since it was virtually impossible to characterise the microstructure without appropriate magnification, this study adopted a technique which was able to examine to a certain degree, the sizes of the bubbles, which enabled to observe the differences effect of the selected parameters. Accepting the stability of foamed concrete as the main criterion for practical purposes, it was crucial to understand the mechanisms that lead to the collapse of air. The basis of the stability measurements the foam stability was evaluated by the drop in foamed concrete height.

9.2 PRACTICAL IMPLICATIONS

Despite the variety of parameters and the complexity of physical phenomena governing its characteristics, this study shows that a few effects can be identified; major trends can be predicted, thus assisting the selection of materials and proportions in achieving predictive capabilities for specific purposes. On a practical basis, corresponding to acceptable flowability range through the Dundee Marsh cone as 1 to 2 minutes, the yield stress was found to be between 6.0 and 8.5 N/m^2. Accepting stability of the foamed concrete mix as less than 5% drop in level, the corresponding bubble diameter was found to be 0.35 mm. Overall, this basic knowledge will significantly benefit accurate prediction of the general behaviour and future practical applications.

9. 3 FUTURE RESEARCH

The findings of this study suggest a number of further avenues for future research. The first of these is an in-depth study of CSA cements, which was found to have resolved instability issues even at lower density. An area recommended for further study is intensive assessment of rheological measurements, using reliable instruments to characterise fresh foamed concrete and relating to its flow characteristics. Another area to study is the examination on bubble sphericity specifically and in general, the microstructure of the whole matrix. A proper magnification technique must be deployed to examine the microstructure of the mixes from the fresh to the harden state. The use of Computed Tomography scan, a medical imaging method that employs tomography, is a possible technique that can examine the bubbles characteristics, namely the bubble diameter. Another point of interest is the blend of CSA and other recycled materials which can be incorporated to further contribute towards sustainable development. Overall, further studies on the performance of CSA foamed concrete is required to develop the use in practical application of CSA foamed concrete mixes.

A second area for future study is the use of foamed concrete in acoustic transmission. Foamed concrete has been established to have excellent thermal and sound insulation properties. Further study will look at the properties of foamed concrete to identify whether it is possible to attenuate sound transmission and the effective range of frequencies. In addition, an area for further attention would be the use of foamed concrete as a composite panel to be sandwiched with normal weight concrete.

A third aspect that would bear further investigation is the development of compatible chemical admixtures and incorporation of fibres. In the current study, the use of chemical admixture was found to have improved one aspect of foamed concrete, namely, its stability whilst reducing the strength. Further improvement is required to improve the use of chemical admixture which will improve the capacity of foamed concrete. With the advancement use of fibres, the study of a wide range of properties and characteristics can further develop an enhanced foamed concrete.

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